AESTHETIC COATINGS FOR STEEL BRIDGE COMPONENTS

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AESTHETIC COATINGS FOR STEEL BRIDGE COMPONENTS

FINAL REPORT

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16. Abstract

The effectiveness of aesthetic coating systems for steel bridges was studied. Twelve 2-coat, 3-coat, and duplex coating systems were selected and subjected to a series of accelerated weathering and mechanical tests to determine their performance. The performance evaluation was made by considering gloss and color retention, coating discontinuities, rust creepage, and coating adhesion. Surface preparation and coating application procedures were given significant consideration. The best color and gloss retention was achieved by the 3-coat fluoropolymer systems, but they required higher materials cost. One of the two 2-coat systems performed nearly the same as the 3-coat polyurethane coating systems and the other showed a poor performance with significant color fading. Duplex polyurethane systems showed comparable performance to that of the 3-coat fluoropolymer systems but they performed better than the 3-coat polyurethane systems. This was primarily due to the added corrosion protection provided by the hot dip galvanization. It was found that proper adhesion in a duplex system can be achieved by following appropriate procedures for galvanization and surface preparation. Both duplex powder coated systems tested in this study experienced out-gassing problems during the initial application and did not show satisfactory performance.

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Executive Summary

This report reflects a study evaluating the aesthetic and durability properties of steel coating systems used in bridge applications. The primary objectives of this study were: 1) to select appropriate aesthetic coating systems for steel bridge application, 2) to conduct accelerated weathering tests to assess the performance of the selected coating systems, and 3) to develop guidelines for selection, surface preparation, and application of coating systems to achieve acceptable aesthetic and durability.

Field visits were conducted throughout Wisconsin on various Bridges. During these visits, performance -related strengths and weaknesses of different coating systems and relevant structural details were identified and evaluated. In addition to the field visits, a literature review was conducted and responses to a questionnaire were evaluated to aid in the selection of appropriate coating systems for this study. Through these efforts, information was gathered on individual coating types, coating systems, surface preparation, application, performance, and accelerated weathering tests. Three types of coating systems were selected for this study: 2-coat zinc-rich systems, 3-coat zinc-rich systems, and duplex systems (coating over galvanized steel). Twelve coating systems were selected for this experimental program. They included:

- Two 2-Coat Systems
    - Both coating systems were comprised of an organic zinc-rich primer and polysiloxane top-coat
- Five 3-Coat Systems
    - Each coating system included an organic zinc-rich primer, an epoxy mid-coat, and a top-coat
        - The selected top-coats included 3 polyurethane and 2 fluoropolymer

- Five Duplex Systems
    - Three conventional liquid coating systems, comprised of a galvanized substrate, a tie-coat, and a polyurethane top-coat
    - Two Powder coating systems, comprised of a galvanized substrate, an epoxy tie-coat, and a top-coat
        - Top-coats included one fluoropolymer and one polyester

Prior to and during application of the coating systems, all guidelines specified by the manufacturers were followed regarding the surface preparation and coating application.

After the selected coating systems reached the required curing state, they were subjected to a series of accelerated weathering tests and other performance evaluations. The accelerated weathering tests included Freeze/UV/Prohesion testing and Xenon Arc testing. The Freeze/UV/Prohesion test assessed the overall durability of the selected coating systems. The Xenon Arc test evaluated the color fading and gloss reduction of the coating systems when exposed to short- and long-wave radiations.

Freeze/UV/Prohesion testing included 15 cycles (5400 hours) of a 24-hour of freeze exposure, a one-week of UV exposure, and a one-week of salt fog exposure for each coating system. After each cycle, the coated samples were evaluated for color fading, gloss reduction, coating discontinuities, and rust creepage. Adhesion and coating hardness tests were conducted initially on control samples for each coating system and on the test samples at the completion of the testing program. The Xenon Arc testing included repeated cycles of 102 minutes of continuous exposure to xenon light followed by 18 minutes of both xenon light and water spray for a period of 15 weeks (2520 hours). After each week of testing, all samples were evaluated for changes in color and gloss. The Xenon Arc tests were performed separately for two different top-coat colors (federal numbers 27038 black and 15092 blue) to determine the effect of color on fading and gloss properties. After completion of the accelerated weathering

tests, the performance of the individual coatings and coating systems were determined and appropriate recommendations made.

From the results of the study, it was found that the best aesthetic performance in terms of color and gloss retention was achieved by the fluoropolymer top coats followed by polyurethane top coats. The best performance in terms of durability was achieved by the duplex systems used in the study. Ideally, it would be expected that the best overall performance for both aesthetics and durability would be achieved by a duplex system with a fluoropolymer top coat. However, the study included only polyurethane top coat in the duplex systems. No fluoropolymer top coat was used in the duplex systems. Accordingly, liquid duplex coating systems are recommended for use on highway and bridge railing. The accelerated weathering test results and field visits suggest that using duplex systems will result in a reduction of overall corrosion. It will also increase the service life of the coating systems and railings. It is also recommended that additional language on surface preparation requirements be added to the WisDOT Special Provisions for galvanized railings when using duplex coating systems. In this study specific guidelines were followed during galvanization and surface preparation of galvanized steel in an effort to enhance adhesion of both zinc to steel substrate and coating materials to the galvanized steel.

Because the galvanization of large steel girders (i.e., plate girders) is generally not practical, 3-coat polyurethane coating systems are recommended for acceptable performance on these structures. Of the two 2-coat systems tested during this study, one performed about the same as its 3-coat polyurethane counterpart and one performed poorly. Therefore, the initial cost savings for using 2-coat systems does not appear to justify the associated risk of poor performance. Similarly, the benefits of color and better gloss retention by fluoropolymer coating systems may not justify the additional associated cost.

Based on the results of this study, recommendations on the selection and application of coating systems were made that may be included in the WisDOT steel bridge coating standard specifications.

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1.0 Introduction

Proper selection and application of an appropriate aesthetic coating can provide protection and maintain good appearance for bridge components for many years. A successful example of good coating performance for a local structure is the Brady Street Pedestrian Bridge in Milwaukee, WI, Figure 1. To reduce maintenance and enhance aesthetic appeal, a white protective coating was applied to both the steel railings and concrete members of the bridge. This coating has helped to protect the bridge from various environmental adverse effects and has added color to increase its aesthetic appeal. The Brady Street Bridge received a design award from the Portland Cement Association (PCA) in 2006, in part due to the coating.

Figure 1: Brady Street Pedestrian Bridge

1.1 Problem Statement

Science, technology, art, and economy are all perquisites for design excellence (1). Due to size, cost, and high visibility, bridges are often seen as symbols of a particular city, town, or community. Enhanced aesthetics can increase the appeal of these structures to the traveling

public and members of the surrounding communities. The use of aesthetic coatings on bridges can also provide additional protection against the environment over their service lives.

Over the past several years, the Wisconsin Department of Transportation (WisDOT) has experienced a number of performance-related issues with aesthetic and protective coatings used on Wisconsin bridge components. These issues primarily include: fading of colors (UV Damage), peeling, blistering, staining, rust bleeding, low resistance to man-made damage (graffiti), unsatisfactory results during repair work, and inadequate moisture protection.

Bridge owners normally make a significant investment in coating materials to enhance the aesthetic and durability of steel bridges and their components. It is expected that these coatings should have reasonably good quality and performance over the relatively long service life of such structures. The life span of a bridge is generally expected to be between 50 and 100 years. The proper application of aesthetic/protective coatings on bridges should help bridge owners to achieve the expected service life and reduce associated maintenance cost.

This research project was intended to evaluate the effectiveness of available aesthetic and protective coating materials for Wisconsin highway bridge applications and to develop recommended specifications and guidelines for future selection and application of such coating materials.

1.2 Background

Based on the review of the available literature and field observations, this study has identified two primary causes of coating failures in bridge applications: ineffective surface preparation prior to application and improper material selection. Through selecting appropriate coating materials and using proper application process, the service life of the

coating can be increased. This will reduce the overall required cost for bridge maintenance, and enhance the longevity of the bridge structure.

The primary problem that results from poor choice and application of coating materials in steel bridges is corrosion of steel substrate. Even partial or local failure of a coating system can cause exposure of steel to harmful environments including exposure to chlorides that result in corrosion. Corrosion affects not only the aesthetics of a bridge, but it can also impact the structural integrity and reduce the overall life span of the structure.

To achieve long term and effective performance of coating materials, several parameters need to be taken into consideration. These include: material characteristics, design and construction aspects, geometrical details, surface preparation, and application.

1.3 Objectives

To achieve proper selection and application of coating systems for Wisconsin highway bridges, this study adhered to the following objectives:

1) Review the available literature as well as current practice and experience with the use of highway related coating materials in Wisconsin, and other states
2) Identify appropriate coating materials that can enhance the aesthetics and durability of steel bridge components over a long period of service
3) Conduct laboratory tests to verify long term performance and quality of the selected materials
4) Develop guidelines and specifications language for appropriate selection, surface preparation, and application of such coating materials
5) Make recommendations for the implementation of the results of this study

1.4 Scope of Work and Research Approach

The objectives of this study were achieved through performing the following tasks:

1) Literature reviews of aesthetic coatings for steel bridge components
2) Survey of WisDOT, other state DOTs, Wisconsin bridge contractors, and coating materials manufacturers
3) Selection of appropriate coating systems after submission of an interim report and consultation with WisDOT
4) Laboratory Testing and Field visits of selected coatings and bridge sites
5) Identification of future research needs
6) Development of guidelines and provision for material selection and application
7) Preparation and submission of a final report

Surveys were sent out to regional WisDOT representatives, other state DOTs, Wisconsin bridge contactors, and coating materials manufacturers to gather additional data on various coatings, their performance, and application procedures. Additionally, several field visits were made to bridges with aesthetic railings. During these visits, coating system failures and structural details were identified. After completing the literature reviews, surveys, and field visits, a work plan was submitted to the Project Oversight Committee (POC) proposing a group of coating systems for laboratory tests, which included outlining the laboratory testing details and the evaluation procedure for the selected coating systems.

The final work plan called for the evaluation of 12 steel coating systems. These coating systems included 3-coat and 2-coat zinc-rich coating systems, duplex liquid coating systems, and duplex powder coated system. The selected coating systems were applied to the appropriate steel and galvanized substrates and their performances were compared using two different accelerated weathering tests: a Freeze/UV/Prohesion test and a Xenon Arc test. The

Freeze/UV/Prohesion test subjected test panels to cycles of Freeze, UV light, and Prohesion (Salt Fog). The Xenon Arc test subjected panels to cycle of Xenon light (full sunlight spectrum). The evaluation criteria used during and after testing included changes in gloss and color, rust creepage, holidays, adhesion, and flexibility. Based on the evaluation results, a recommendation of surface preparation, application, and coating selection was given to the Wisconsin Department of Transportation.

2.0 Literature Review

A literature review was conducted to gather information on aesthetic coatings used for bridge components. The literature review allowed the research staff to identify and evaluate various types of coating systems, surface preparation procedure, and application procedures.

2.1 Coatings

Powder and traditional liquid coatings are two types of coating used for aesthetic and protection of steel structures. Although traditional liquid coatings have been the coating of choice for many bridges, powder coatings can offer some benefits over traditional liquid coatings. In most cases it is not practical or economical to apply powder coating on large steel bridge components (i.e., girders), but smaller items like railings may benefit from powder coating.

2.1.1 Liquid Coatings

Liquid coatings are typically comprised of binders/resins, pigments, solvents, and other additives. Binders/resins form the matrix of a coating. They are film forming agents that bind everything else in the coating together (2). Different coatings or paints are usually named after the type of resin used. Common types of resins used for liquid coatings include: alkyds, polyurethanes, epoxy, chlorinated rubber, polyesters, silicones, and acrylic.

A pigment is comprised of a solid particulate material which is dispersed in the binder (3). Pigments in coating systems generally break down into three categories including: primer, functional, and extender pigments. Primer pigments can provide aesthetic appeal to a coating by providing color, opacity, and protection from UV light. These materials are typically comprised of titanium oxide and iron oxide. Functional pigments such as zinc, aluminum, ferrous, and calcium in the forms of phosphates, borates, and molybdates are communally used

for their anticorrosive properties. Zinc is a common functional corrosion protecting pigment used for bridge coatings (4). Added to primers in bridge coatings, it serves as a sacrificial barrier to protect a given substrate. These types of pigments dissolve slowly in a coating which allows them to provide corrosion protection. Finally, extender pigments are used to build pigment volume and can consist of carbonate and silica (4).

Pigments can also be used to offer protection against UV degradation. By selective absorption, certain pigments can absorb UV light that would normally attack light sensitive coatings. Typical absorption pigments include: zinc oxide, zinc sulfide, red iron oxide, carbon black, and rutile titanium dioxide. Pigments such as anatase titanium dioxide can make degradation worse through photocatalytic degradation (5).

Solvents are added to reduce the viscosity of the binder and other components of the coating. Solvents dilute the coating allowing for homogeneous mixing and application to the surface of a substrate in the form of a thin smooth film. Solvents are becoming an increasing environmental concern due to the Volatile Organic Compounds (VOCs) that they release into the environment. Water-borne systems can be used as an alternative to the conventional solvent-borne coating systems, because they allow better particle dispersion within the resin in a coating.

The final main component of a coating may be other additives. Additives can be formulated into a coating for variety of purposes. Several of these purposes include: drying additives, heat resistance additives, mildew inhibitors, and adhesion promoting additives. Depending on the desired properties of a coating, different additives can be used in the coating.

2.1.1.1 Zinc-Rich Coatings

There are two general types of zinc-rich coating systems for steel: inorganic and organic zinc. These coating are usually applied directly to the metal as a primer. The zinc-rich primer is

used in a multi coating system, normally involving two- or three-coat layers. Zinc-rich coatings provide a more reactive anode in electrical contact with the metal sensitive to corrosion attack (5). This cathodic protection property of zinc-rich coatings acts a sacrificial barrier of protection to exposures of moisture that cause corrosion of the steel substrate. Zinc-rich coating systems help in the elimination of pitting and sub-film corrosion, even at points where voids, pinhole, scratches, and abrasions in the coating already exist (6). The high level of anticorrosion behaviors displayed by inorganic and organic zinc-rich coatings is one of the main reasons they are used frequently in steel bridges.

One way to categorize zinc-rich coatings is based on the type of resin/binder material used. The organic zinc coatings contain zinc metal pigments that are mixed into an organic paint binder (7). Organic zinc-rich coatings are comprised mainly of epoxy, polyamide, urethane, vinyl and chlorinated-rubber binders. Properties of a zinc-rich coating depend on the type of binder used to create the coating. For instance, the heat resistance of thermo set epoxies and urethanes is superior to that of chlorinated rubbers and thermoplastic vinyls. Additionally, dry hardening and curing of the zinc-rich coatings is also affected by the type of binder used (6). One important advantage of organic zinc-rich coatings is their ability to be more tolerant to deficient surface preparation and application. Organic coatings wet-out more readily on the substrate and have the ability to be coated where residues of old paint and rust remain (6).

Inorganic zinc-rich coatings comprised of a zinc metal powder mixed into an inorganic silicate paint binder. The binder for these inorganic coatings can be either water-borne or solvent-borne. The Society for Protective Coating categorizes inorganic zinc-rich coatings into three groups: post-cured water-borne alkali metal silicates, self-cured water-borne alkali silicates, and self-cured solvent-borne alkyl silicates. The binder for all three of these categories is inorganic zinc, but the curing methods are different. An advantage of inorganic zinc-rich

coatings is that they can provide somewhat longer galvanic protection than their organic counterparts, but they are not as tolerant to deficient surface preparation and application. In addition, inorganic zinc-rich coatings are more heat resistant than organic zinc-rich coatings and have better abrasion and impact resistance (6).

2.1.1.2 Epoxy Coatings

The properties of epoxy coatings include: strong adhesion to most surfaces, corrosion resistance, resistance to solvents and chemicals, resistance to abrasion, and oxygen impermeability. A major attribute of epoxy coatings is its adhesion properties. The adhesion strength of epoxies can range from 1,500 to 4,600 psi (8). Epoxy coatings generally are not resistant to UV light and begin to chalk and degrade over time. When exposure to UV light is expected during the service life, an epoxy coating is generally used as a primer or intermediate coat (9). Commonly, epoxies used for metal surfaces have been solvent-borne coatings.

2.1.1.3 Polyurethane Coatings

Polyurethanes were first created more than 50 years ago and can now be formulated to have a variety of properties that include: light stability, abrasion resistance, and solvent/chemical resistance. Polyurethanes can be used in a number of coating configurations with many different properties. Polyurethane coatings are made from resins that are formed from the reaction of isocyanates with hydroxyl containing compounds, also known as polyols (10).

The selection of isocyanates and polyols types in creating polyurethane coatings can have a significant effect on the properties of the final coatings. Also, specific properties may be achieved based on selecting aromatic and aliphatic isocyanates. The most common aromatic isocyanate groups include toluene diisocyanate (TDI) and diphenylmethane diisocyanate (MDI), and the most common aliphatic isocyanates include hexamethylene diisocyanate (HDI) and

isophorone diisocyanate (IPDI) (5). Although aromatic isocyanates polyurethane coatings offer excellent hardness and heat resistance, they tend to discolor and chalk when exposed to sunlight (5). By contrast, aliphatic isocyanate polyurethane coatings provided excellent color and gloss properties (11). Although aliphatic polyurethanes are typically used as top-coats in coatings systems due to their good weathering characteristics, there is a potential safety concern due to the chemical reaction of isocyanates within the polyurethane coatings.

2.1.1.4 Fluoropolymer Coatings

Fluoropolymer coatings have been used for more than 40 years due to their strong physical properties including: excellent long term color and gloss retention, and outstanding corrosion, abrasion, temperature, and chemical resistance (12). They normally outperform polyurethane coatings in terms of color and gloss retention. It has been indicated that fluoropolymer coatings will not need to be re-applied for 20 years compared to 10 years for polyurethane coatings (12). The main disadvantage to fluoropolymer coatings is their relatively higher cost. Cost for fluoropolymer coatings can be approximately 5 to 10 times that of urethane coatings.

2.1.1.5 Polysiloxane Coatings

Polysiloxane coatings were developed and patented in the early 1990's (13). Polysiloxane coating are typically used in 2-coat systems that includes a zinc-rich primer and a polysiloxane top-coat. The strong chemical bond between silicone and oxygen within these coatings make them highly stable. This characteristic allows polysiloxane coatings to have good gloss and color retention, corrosion resistance, and chemical resistance. Polysiloxane coatings are expected to have equivalent or better UV protection compared to urethane coatings, and should have better long term gloss retention compared to urethane coatings (14). Polysiloxane coatings can be formulated with as much as 90% solids, which reduces the amount of required

solvents, and in turn, can reduce the VOC contents in these coatings. Along with a lower VOC content, polysiloxane coatings are formulated with no isocyanates, which are a safety concern in polyurethane coatings.

Early polysiloxane coating materials often brittle and suffered from internal stresses which resulted in numerous field failures. These failures included instances of poor adhesion and also brittleness in the coating (13). The new generation hybrid polysiloxane are expected to have solved the deficiencies of the earlier polysiloxane coatings. However, some of the new coatings do not have records of field performance to verify their performance. Polysiloxane coatings have performed well in controlled laboratory testing, but their performance has not always transitioned well into the field (13).

2.1.2 Powder Coatings

Powder coatings are made up of finely ground particles of resins, pigments, and various additives. Because powder coatings are applied as a dry powder they are free from solvents in contrast to liquid coatings. The absence of solvents in powder coatings gives these types of coatings near zero VOC emissions.

Resins used in powder coatings are either thermoplastic or thermosetting resins. Thermoplastic resins are classified as lacquers and will melt and flow when sufficient heat is applied to the mix. For these resins, a sufficient level of heat causes a chemical cross linkage in addition to the melting and flow of the mix. Upon application and heating, thermoplastic powder coat particles melt and form a continuous paint film with a uniform chemical composition after a cooling period (15).

Thermosetting powder coatings are more commonly used and classified as enamels. When heated, they are cross linked to form a thermosetting paint film with a different chemical structure. The cross link reaction in thermosetting powder coating takes place between a main

resin component known as a cross-linker and another resin component known as a cross-linkage. Thermosetting powder coatings have a more functional use for industrial and outdoor applications. Different types of thermosetting powder coatings include; acrylics, epoxies, epoxy polyester hybrids, fluoropolymers, polyesters, and vinyls (15).

2.2 Steel Protective Coating Systems

A coating system consists of multiple layers of different individual coatings. Each coating serves a different purpose in the coating system. Zinc-rich coating systems (2- or 3-coat) and duplex coating systems (painting over galvanized steel), are commonly used for aesthetic and protection of steel bridge components. There are other coating systems in the market, but this study has focused on 2- and 3-coat zinc-rich coating systems and duplex systems.

2.2.1 Zinc-Rich Coating Systems

The 3-coat zinc-rich coating system has been the system of choice for protecting steel bridges from corrosion. A 3-coat system usually consists of a zinc-rich primer (organic or inorganic), an epoxy or urethane intermediate coat, and an aliphatic urethane top-coat. A 2-coat system consists of a zinc-rich primer and a fast drying high-build top-coat. Three main types of top-coats in the 2-coat systems are: a polyaspartic coat, a polyurethane coat, or a polysiloxane coat (7).

Top-coats are added to zinc-rich systems to help with aesthetics and to protect against atmospheric chemicals and UV exposures. Zinc coating systems without a top-coat have a limited pH range of 5 to 10. A top-coat can increase the pH range of a zinc-rich system to provide better chemical resistance. Additionally, top-coats can be used for aesthetic purposes. They can protect against the dull and gray appearance as well as white salts that will eventually form on the surface when a zinc-primer weathers (16). Top-coats can also be formulated in different colors to improve the bridge aesthetics as desired.

Two-coat systems reduce cost in painting materials, down time due to painting, and more importantly reduce labor costs (17). Normally, 2-coat systems have dry film thickness equivalent to a 3-coat system, so the advantage is in reduction of labor cost and drying times by eliminating one additional layer of coating. Proper application and coverage is particularly important with 2-coat systems. When coating a larger structure with hard to reach areas, i.e. underneath flanges, tight details, and on edges, the margin of error is smaller using a 2-coat system instead of a 3-coat system.

Various studies have produced mixed results regarding the performance of 2-coat coating systems compared to other types of systems. Results from a 2006 study , as published in the Journal of Protective Coatings and Linings, show that 2-coat painting systems for steel bridges had a performance that was similar to or inferior to those from the conventional 3-coat systems (17). The study concluded that the performance of the 2-coat systems may be taken to be equivalent to that for 3-coat systems without sacrificing the corrosion resistance properties. A more recent study, performed by researchers at the Federal Highway Administration, evaluated the performance of 1-coat systems against 2- and 3-coat systems that were used as control systems in the study (4). This study concluded that the 2-coat control system performed poorly and assigned it a low overall ranking.

Field performance of 2-coat systems has not always matched the acceptable laboratory testing results. In addition, some of the 2-coat systems were introduced relatively recently within the coating industry and have not had the records of satisfactory field performance because their limited time of outdoor exposure.

Many state DOTs, including the Wisconsin DOT, list 2-coat systems on their qualified product list (19). This may change as more information on the performance of 2-coat systems becomes available to bridge owners. The Northeast Protective Coating Committee (NEPCOAT),

which represents several northeastern states in the U.S., included a 2-coat system on their qualified product list until 2010, when it was removed due to performance related concerns (18).

2.2.2 Duplex Systems

A duplex system refers to a coating that is applied over a galvanized steel substrate. Similar to 2- and 3-coat coating systems, duplex systems are applied as a system of layers of coatings. A common duplex system is made up of a urethane or epoxy tie-coat and an aliphatic urethane top-coat. The tie-coat in a duplex system is intended to increase film thickness and to allow proper adhesion of the top-coat. The top-coat of a duplex system is typically the same as a top-coat used in a conventional 3-coat coating system.

The primary difference between a duplex system and a 3-coat system is the galvanization of the substrate steel. In a duplex system, the galvanization replaces the zinc-rich primer used in the 3-coat system. In a duplex system, the zinc-iron layer acts as an anode to offer a sacrificial barrier for protection of the underlying steel.

In a duplex system, the coating over the galvanized steel acts as an extra barrier of protection and slows down zinc consumption in the galvanized steel, which can extend the life of the galvanized steel. Also, the top-coat can add color to the galvanized steel and enhance the aesthetic value of the structure. When un-galvanized coated steel begins to corrode, rust forms under the coating and will eventually cause undercutting of the coating film that will lead to pealing of the coating. However, in a galvanized steel the zinc corrosion is minimal and the peeling is minimized. In addition, galvanization eliminates early rusting from pin holes or discontinuities that can form in coating layers due to less than optimum applications (20). Unlike liquid coatings where surface tension forces lead to reduced coating thickness at sharp edges and corners, galvanized coatings form a thicker layer of protection at the edges and corners due

to the diffusion reaction between zinc and the base steel (20). This results in a better protection of steel structures along edges and corners where the likelihood of corrosion is higher. .

2.2.2.1 Hot-Dip Galvanization

Hot-dip galvanization involves adding a layer of zinc protection to the steel surface. A typical hot-dip galvanization process includes a caustic cleaning, a water rinse, an acid bath, another water rinse, a pre-flux, and a zinc bath. The caustic cleaning process involves a hot alkaline solution bath that removes organic contaminants like dirt, grease, and oil. The acid bath removes any mill scale and left over rust on the steel. The fluxing step removes any oxides and prevents any oxides from forming prior to the galvanization. The flux also helps to promote bonding of the galvanizing zinc to the steel surface. The pre-flux consists of exposure to a solution of zinc ammonium chloride. The steel is then dried prior to emersion into the molten zinc (21).

During the final step of the galvanization, the steel is immersed in a solution consisting of a minimum of 98% zinc. The chemical composition of the molten zinc bath is specified by ASTM A123. Items are dipped into molten zinc that is kept at approximately 443°C (830°F). After the items reach the bath temperature they are slowly removed from the molten zinc and drained to remove any excess zinc. The samples are then allowed to air cool to ambient temperature.

The molten zinc bath provides a physical bonded coating to the steel substrate in the form of a series of zinc-iron alloy layers and a surface layer of pure zinc. Starting at the substrate steel and working to the outside surface, these layers consist of the following: gamma layer (75% Zn, 25% Fe), Delta layer (90% Zn, 10% Fe), Zeta layer (94% Zn, 6% Fe), and Eta layer (100% Zn). Hot-dip galvanization is limited to the size of the zinc bath/kettle. A kettle 60 feet long by eight feet deep is the most common in North America (21). As such, hot-dip galvanization, or

subsequently duplex coating systems, are limited to structures that are not very large. For example, structures such as bridge railings are more suitable for such applications than large steel plate girders or other large structural members.

2.3 Surface Preparation

A key factor in the overall performance of an effective and successful coating system is the adequate adhesion of coating layers to the substrate and other coating layers (2). Adhesion refers to chemical and physical reactions at the interface of the substrate and the coating. Regardless of the system used, if the coating does not properly adhere to the substrate it will not meet its intended purpose and the service life span will decrease. Surface preparation is one of the most important factors for proper adhesion of a coating layer to the substrate. Depending on the type of substrate and application requirements, an appropriate surface preparation must be performed.

2.3.1 Steel Surface Preparation

For steel structures, surface preparation along with proper coating application are the two most important factors for creating a high quality coating product (22). Along with a clean surface the steel must have the correct roughness or anchor pattern to allow for proper adhesion. Surface preparation for steel varies between existing steel structures and new steel structures. For the coating of steel structure, the Society of Protective Coatings (SSPC) and National Association of Corrosion Engineers (NACE, International) have jointly developed surface preparation for different conditions. One important requirement for steel surface preparation is its cleanliness. Proper cleanliness for steel includes; removal of all mill scale, grease, dirt, rust, and other contaminates before application of the first layer of coating.

To achieve the proper surface preparation, the SSPC recommends several methods. The most common surface preparation specified for bridge use is SSPC-SP 6/ NACE No. 3:

“Commercial Blast Cleaning” which also requires SSPC -SP1: “Solvent cleaning” (22). SSPC-SP1 denotes solvent cleaning of the surface prior to all other cleaning operation. SSPC-SP 6 standard denotes commercial blast cleaning of the steel surface until two-thirds of the surface is free from all visible residues with only staining permitted on the remaining surface area (23). This standard states that the resulting surface should be free of oil, grease, dirt, all rust, mill scale, paint, and foreign matter. Blast cleaning has several different specifications on cleanliness of a surface. These specifications include: “White Metal Blast Cleaning” (SSPC-SP 5/NACE No. 1), “Near-White Blast Cleaning” (SSPC-SP 10/NACE NO.2), “Commercial Blast Cleaning” (SSPC-SP6/NACE No. 3), and “Brush Off Blast cleaning” (SSPC-SP 7/NACE No. 4) (22). With the proper surface preparation the coating is expected to achieve a better adhesion to the substrate and to offer a better overall performance.

2.3.2 Galvanized Surface Preparation

One of the most important factors for painting over galvanized steel is the surface preparation. The American Galvanizers Association (AGA) suggests that surface preparation for galvanized steel be done within the first 48 hours or, alternatively, after a full weatherization cycle, which normally occurs between 1 and 2 years after the galvanization process.

Fully weathered galvanized steel offers the easiest surface to paint which can extend the service life by developing a corrosion protection system (24). By contrast, partially weathered galvanized steel surface (from 2 days to 1 year after galvanization) is the most difficult to prepare for painting. Partially weathered galvanized steel develops a zinc patina surface deposit that is made up of zinc oxide and zinc hydroxide. These particles are loosely formed on the surface and need to be removed to ensure acceptable adhesion of the first layer of coating material. During this period, proper surface preparation is important for achieving a successful duplex system. In the time between one and two years, this zinc patina fully forms and tightly

adheres to the galvanized steel (forming a fully weathered surface), allowing the paint to be applied directly to a clean surface (20).

In addition, eliminating the water quenching or chromate treatment by the galvanizer can increase the adhesion of the paint to the galvanized surface in a duplex system (25). In most cases the water used in quenching can contaminate the galvanized surface. Also, the quenched water is sometimes treated with chemicals, such as 0.2% sodium dichromate, which leaves a film on the galvanized substrate and can affect the adhesion of a coating to the surface (25).

The SSPC recommends a specific standard for surface preparation for galvanized steel. The specification for galvanized steel is SSPC-SP16 “Brush-Off Blast Cleaning of Coated and Uncoated Galvanized Steel, Stainless Steels, and Non-Ferrous Metals”. This standard requires a solvent cleaning following SSPC-SP1 prior to brush off blasting. The standard also lists specific requirements for the removal of wet storage stains, and that galvanized steel should be free from chromates and other passive treatments. Additionally, the standard requires the use of softer abrasives and relative low air pressure to allow the zinc layers to remain intact during the brush-off blast cleaning (26).

The SSPC recommends sweep blasting of galvanized steel to remove loose zinc compounds and not the zinc metal layer. Oxides that loosely form on the surface can be removed with a sweep blast, which in turn provides a light surface profile that promotes adhesion of the first layer of coating. The American Galvanizers Association (AGA) recommends sweep blasting at an angel of 30 to 60 degrees to the surface rather than the standard blasting procedure that is performed at a 90 degree angle. The sweep blasting should be done with softer abrasives with an air pressure of approximately 40 psi. Sweep blasting abrasives that have been used successfully include: aluminum/magnesium silicate, mineral sands with Mohs hardness of five or less, organic media such as corn cobs or walnut shells, and stone materials

such as corundum or limestone (24). Additionally, angular iron blasting grit is not recommended under any circumstances due to the increased possibility of damage to the zinc coating (27). Sweep blasting of a galvanized surface removes oxides from the surface and provide a light surface profile. These oxides are loosely adhered to the galvanized surface and do not require the same blasting procedure needed to remove mill scale from an un-galvanized steel substrate.

2.4 Application

Besides poor surface preparation, factors such as inadequate coating thickness, improper mixing, and deficient curing can cause coating related performance problems (28). A failed coating can also result from an improper coating application process even with a proper surface preparation. Some coatings require a certain temperature, humidity, and dew point to achieve proper curing. It is important to follow manufacturer's specifications to make sure that the coating is applied under correct conditions.

2.4.1 Liquid Application

There are three main types of liquid coating application: brush or rolled, conventional air atomizing spray, and airless spray. For brush and rolled application, the paint is mixed and either applied with a brush or roller. In this application it is difficult to get a precise and uniform film thickness. Conventional spray consists of atomizing the paint into a mist and applying it to the surface of the substrate. Paint is supplied to a fluid nozzle in the spray gun by the means of a gravity feed, a pressure system, or by siphoning. The fluid nozzle is equipped with a fluid needle that delivers a controlled stream of paint. Compressed air is directed to the paint stream in the air nozzle producing an atomized mist. It is important that the compressed air is oil, dirt, and water free during application (15). The atomizing process allows the paint to be applied in uniform fine finish, creating an aesthetically appealing appearance.

Airless spray also involves atomizing the paint, but instead of using compressed air it uses a high fluid pressure system. The paint is pressurized anywhere from 500 to 6,000 psi depending on the type of paint. The pressurized paint is then supplied to the airless spray gun for application. When the pressurized paint exits the fluid nozzle in the spray gun it expands slightly and encounters air resistance. This process atomizes the paint into small droplets without the means of compressed air (15). Airless spray achieves a more efficient process by reducing the amount of overspray compared with conventional compressed air spray.

2.4.2 Powder Coating Application

The most widely used methods for powder coating application include; fluidized powder-bed, electrostatic fluidized-bed, and electrostatic powder spraying. Of these three methods electrostatic powder spraying is the most common. When applying electrostatic powder spray, parts must be electrically grounded for proper application. Powder stored in a feeder unit is pumped from the feeder to the electrostatic powder gun. During this process the powder is transformed into a fluid-like powder cloud. The powder gun supplies an electrostatic voltage to the powder that creates diffused electrically charged powder particles that are attracted to the grounded parts, thus creating a layer of powder or coat (29). After application of the powder coating, the parts are heated to allow the powder coating to melt, flow, and cure to a continuous paint film. Gas or electric heat can be used in addition to infrared radiation. The duration of heating depends on the type of coating and also the size of the part being powder coated.

One type of problem that occurs during the application of powder coated galvanized steel is out-gassing. During the curing stage oxides on the galvanized steel may release water vapor or air causing craters or blisters on the surface of the powder coat. The galvanized steel may also release gas due to trapped air or water in the galvanized coating. Water and air can

penetrate small crevices in the outer most layer of the zinc and become trapped. When the powder coating is heated during the curing stage, the air and water turn into a gas which releases through the powder coating causing small craters (30).

Out-gassing can also be attributed to the formulation of the powder coating, especially polyester powder coatings. Discrete polyester resin particles in contact with the galvanized steel surface do not fuse at the same time as those on the surface of the polyester powder. The cause of this is attributed to the mass of the galvanized steel and time it takes for the galvanized steel to come up to fusion temperate. Resins formulated with anti out-gassing agents have been used to remedy this problem. Several methods for reducing the out-gassing problem include: a light sweep blast of the galvanized surface prior to application, pre-heating galvanized steel prior to application, and setting a minimum curing temperature for the specific powder coating (30).

2.5 Accelerated Weathering

Since natural outdoor weather exposure is time and cost extensive, accelerated weathering tests are performed to evaluate the performance of coated laboratory samples. As such, selecting an appropriate accelerated weathering program is critical to obtaining results comparable to those from normal outdoor exposure. This study used a program of accelerated weathering exposure to allow meaningful comparison of coating systems' performance on test samples.

2.5.1 ASTM Standard D5894-10, Freeze/UV/Prohesion

Various accelerated weathering tests have been used in the coating industry to evaluate the performance of different coating systems. One test method frequently used by the U.S. Federal Highway Administration (FHWA), North East Protective Coating Committee (NEPCOAT), and National Transportation Product Evaluation program (NTPEP) is the ASTM Standard D5894-

10: “Standard Practice for Cyclic Salt Fog/UV Exposure of Painted Metal”. ASTM D5894-10 requires weekly cyclical exposure of the coated test samples to UV/Condensation and Salt/Fog.

The UV/Condensation exposure includes cycles of 4 hours of UVA light with no condensation and 4 hours of condensation with no UVA light. For the cycle without the condensation, the UVA light is set to a wavelength of 340nm with an irradiance of 0.89 W/m^2nm and a temperature of 60°C. During the condensation cycle, the temperature is set at 50°C. The Fog/Dry exposure cycle includes 1 hour of fog exposure at ambient temperature followed by a 1 hour dry-off at 35°C. The salt fog cycle is composed of exposure to a fog from a solution of 0.05% by weight sodium chloride and 0.35% by weight of ammonium sulfate (31).

2.5.2 ASTM Standard D6695-08, Xenon Arc

Another type of accelerated testing used in evaluation of coating systems is exposure to certain UV light in a Xenon Arc testing equipment. One specific Xenon Arc test is based on the ASTM Standard D6695-08: “Standard Practice for Xenon-Arc Exposure of Paint and Related Coatings” (32). This test determines the effects of Xenon light on a coating system. Xenon arc exposure is different from UV light in that it replicates the full sunlight spectrum, instead of exposure to the UV light only. Along with UV light, Xenon light also produces longer wave lengths including infrared and visible light. Under ASTM Standard D6695 test panels are subjected to cycles of 102 minutes of continuous light, followed by 18 minutes of light with water spray (32). A reference black panel is used in the Xenon Arc equipment chamber with a temperature set at 63°C with an irradiance set at 35 W/m^2nm.

2.6 Coating Structural Details

The structural details and geometry in bridges can play a significant role in the successful performance of a coating system. Structures with many corners, edges, crevices, and moisture traps increase the possibility of a coating failure. Sharp edges are a concern because of

the decreased coating thickness on these edges. Many coatings exhibit considerable surface tension when drying. This causes coating materials to pull away from sharp edges and interior and exterior corners during the drying process resulting in coating failures in these areas (10). Interior corner are also areas where moisture, deicing chemicals, and debris can accumulate and collect over time. These areas create a more severe environment that increases the chance of localized coating failures.

Hard to reach areas within a structure make proper application of coating materials difficult and this may lead to improper coating thickness or improper surface preparation. When possible, it is best to design and build a structure that has fewer of these problem areas, which in turn will increase the chance of success for the performance of the coating system.

Welds also are areas of concern when coating. Welds create irregularities in the steel structure that can lead to coating failures if proper surface preparation and application are not followed. One of these irregularities is weld spatter. Weld spatters are small nonmetallic particles that are expelled during the fusion of the weld and base metals. These ball-liked particles reside on the surface near the weld and cause the coating to flow away and become thin in these areas. Also, during the welding process undercutting or voids may be created at the toe of the weld that can cause difficulties during the coating application (10). To enhance the effectiveness of coating systems, it is important to remove weld scale, slag, and spatter before application of a coating.

2.7 Corrosion

Along with improving aesthetics, a protective coating must be able to protect the substrate from corrosion. One of the main failures of an ineffective coating system is the corrosion of the underlying steel. Corrosion of steel can lead to rust bleeding and staining that greatly degrade the aesthetic value of the structure. An example of a coating failure leading to

poor aesthetics of a bridge is shown in Figure 2. Here, poor geometric details of the railing lead to a coating failure, which caused rust bleeding and staining of the concrete parapet.

Figure 2: Sauk City, WI Bridge

For most metals, the corrosion is an electrochemical process. In this process, the presence of several elements allow corrosion to take place. These elements include: an anode, a cathode, an electrolyte, and an external contact between the anode and cathode. With these four elements in place, a corrosion cell forms allowing corrosion to take place and advance. Another element that is generally required for the corrosion process is oxygen. Although the corrosion process may begin without oxygen, the process will slow down or stop all together in the absence of oxygen (10).

Not only can corrosion affect the aesthetics of the underlying steel, it can also be detrimental to the structural integrity of bridge members, which can be very costly. A 2002 study by the Federal Highway Administration estimated that the total direct cost of metal corrosion in the 26 industrial sectors in the U.S. to be $276 billion per year (33). In 2012 the American Society of Civil Engineers (ASCE) issued a report on the nation's infrastructure and gave bridges an overall rating of "C^+." ASCE found 24.9% of the nation's bridges to be functionally obsolete or structurally deficient, and recommended that $20.5 billion in annual

investment will be needed to eliminate the bridge deficient backlog by 2028. ASCE also noted that 5.5% of Wisconsin's bridges are functionally obsolete and 8.2% are structurally deficient (34). Although all obsolete and deficient bridges do not suffer primarily from coating failures, a successful use of effective coating systems can improve the appearance and durability of many of our bridges.

2.8 Volatile Organic Compounds (VOCs)

The release of Volatile Organic Compounds (VOCs) from coating materials in the air is a safety and environmental concern. Pollution caused from VOCs can have a negative impact on the environment and are therefore regulated. Over the years, the applicable regulations on VOCs have become more stringent due to the increased environmental awareness. VOCs are defined by the Environmental Protection Agency (EPA) as "any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate, which participate in atmospheric photochemical reactions."

Many structural/architectural coatings used for bridges and their components are comprised of organic solvents. Most of these organic solvents are made up of VOCs which have a relatively high vapor pressure under normal atmospheric and temperature conditions. After application of these coatings they begin to cure and the organic solvents begin to evaporate into the atmosphere. Due to the high vapor pressure, VOCs easily evaporate into the atmosphere, and act as air pollutants in the form of smog or low level ozone (35). This ozone is formed when the VOCs react with nitrogen oxide and sunlight in the atmosphere.

Because of the harmful effect on the environment, the EPA's clean air act places regulations on the amount and types of VOCs that can be used in architectural coatings. Various states and agencies have even more stringent rules that govern the permitted volume of VOCs in coatings, with California being one of the strictest.

Due to regulatory environmental limitations on the level of the Volatile Organic Compounds (VOCs) in coating systems, waterborne paints/coatings are being used as a substitute to the traditional solvent borne paints. Waterborne coatings offer the advantages of reduced toxicity, lower odor, easy/safe clean up, lower VOC emission, and less hazardous waste disposal. Disadvantages can include requirements for more surface cleanup, unavailable resins for all waterborne formulas, longer drying times, and cost.

3.0 Survey Results and Field Visits

As required by this study (Task 2 of the Scope of Work), three different questionnaires were prepared and distributed among all regional maintenance personnel of WisDOT, various U.S. State Departments of Transportation, and various coating systems manufacturers. A questionnaire was also prepared and distributed among Wisconsin bridge contractors but it is not included in this report because only one response, which was incomplete, was received. The surveys were done in an effort to acquire necessary knowledge regarding common materials and application processes as well as performance of coating systems that are used for bridge components (i.e. handrails). The study's Project Oversight Committee (POC) discussed and approved the contents of the questionnaires before their distribution. Complete questionnaires and responses are shown in Appendix A.

3.1 Summary of Regional WisDOT Responses to Questionnaire

Not all of the WisDOT regional offices had records on the performance of steel railings used in their bridges. It was discoveredd that some structures in the Southwest region of Wisconsin (Lacrosse area) have had significant problems with the performance of 2-coat systems for steel handrails, but fewer problems with paint systems over galvanized steel. It was also found that coatings on steel railings in salt spray zones (i.e., in the direction of travel of the snow plow during the winter months), have shown greater deterioration. In addition, it was found that poor structural details have contributed to unsatisfactory performance of the coating systems applied to bridge handrails.

3.2 Summary of Manufacturers Responses to Questionnaire

Only partial responses to the questionnaire were provided by some of the manufacturers that were contacted. However, all who responded were willing to offer detailed

information on their coating products in person or via phone with the research staff. Responses from the manufacturers included the following:

- If applied correctly, 2-coat systems should offer satisfactory performance. However, with only two layers of coatings there is a greater probability that some parts of the substrate may not get the proper coating coverage.
- When 3-coat coating systems are applied, a more effective coverage of the substrate can be achieved with one additional layer of coating in the system. A 3-coat coating system is less susceptible to coating application errors than a 2-coat system.
- For duplex systems, the most critical factor for successful performance of a coating over galvanized steel is the surface preparation. Insufficient or improper surface preparation can lead to adhesion problems and peeling of the coating layer over the galvanized steel.
- Selection of appropriate coating system for specific applications and environment as well as application by skilled operators can influence the successful performance of coating systems.
- Additional coating systems were identified by the manufacturers for possible inclusion in the study. These systems were discussed with the project oversight committee and were considered for possible future testing.

3.3 Summary of Various State DOTs Responses to Questionnaire

A questionnaire was distributed among various state DOTs with similar climates to Wisconsin, as well as those with structures subject to harsh environments. Responses varied among the State DOTs, with some providing complete information and some providing only information regarding their specifications and provisions. It was reported that some states specify approved coating systems for steel railings based on the requirements of the NEPCOAT.

Most states reported that they use a 3-coat painting system, consisting of a zinc primer, an epoxy mid-coat, and a polyurethane top-coat, for steel railings. Another system used consisted of galvanized steel railings with or without additional coats of paint. When an additional coating is applied to the galvanized steel, most respondents required special provisions for surface preparation for the galvanized steel.

Both the New Hampshire DOT and the Virginia DOT have provisions stating that the galvanization process shall not be water quenched or chromate treated by the galvanizer. Eliminating these processes achieves better adhesion of the paint to galvanized surfaces. The Virginia DOT also uses powder coating over galvanized railings with provisions that require the first coat over the railings be applied within 12 hours of the galvanization process.

3.4 Field Visits

During June 2011, an inspection was conducted in collaboration with WisDOT SW Region Bridge Maintenance and Inspection Office on various decorative hand railings. Three bridges with hand railings were identified that had mixed performances of the handrail coating systems. Two railings were coated with 3-coat painting systems applied over bare steel. Both railings had significant rust bleeding at the connections of adjacent railing sections, along with fading of the top-coat. The rust bleeding stained the concrete parapet located below. Color fading in the hand railings was more noticeable in red color top-coats than in black top-coats. The red fading was also more noticeable due to contrast between the original railings and the areas of the railing that had been “touched-up” over the years.

The third railing included a 2-coat system applied over galvanized steel. This system with a black top-coat had similar fading as the black 3-coat system, but there was no rust bleeding at the connections of adjacent railing sections. This is attributed to the additional protection offered by the galvanization process.

During July 2011, another inspection was conducted at a bridge located in northern Wisconsin. This bridge had coated galvanized steel railings. There were no known problems with these railings, but the railing has complex structural details in comparison with other galvanized railings in Wisconsin bridges.

Working with John Bolka, WisDOT SE Region Structures Maintenance Engineer, another bridge was identified to have problems due to corrosion of railings within only a few months of the initial construction. During November 2011, an inspection was conducted on the bridge to examine the coating performance problems for the railings of this bridge. This bridge had a galvanized railing with a 2-coat duplex system applied over the galvanization. These field inspections are discussed in further details below.

A final bridge was inspected in Beloit, Wisconsin. This bridge had galvanized aesthetic railing with a duplex coating system and a green top-coat. This bridge had no rust bleeding at the ends of the railings. In addition, areas of the bridge that had been damaged down to the galvanized substrate showed no signs of corrosion. There was also noticeable color fading and loss of gloss on the railings.

3.4.1 Baraboo Bridge

The Baraboo Bridge (B-56-153) is located in Sauk County, Wisconsin, on US Highway 12 crossing the Baraboo River. This bridge was constructed in 2000. This bridge received decorative railings with a 3-coat zinc-rich paint system that had a red brick tone colored top-coat. This bridge railing has encountered several problems due to failure of the coating system and poor structural details. Throughout the bridge railing, the red top-coat showed significant signs of fading. The color on the railings faded to a light pink/purple color. The color fading was more prominent in areas where fresh touch up paint was applied to repair physical damage on

the coating. The top-coat on some areas of the railing with the east side sun exposure has been peeled off and leaving only the white epoxy mid-coat exposed, shown in Figure 3.

Figure 3: Baraboo Bridge Railing Top-Coat Failure

An additional problem that affected the aesthetic of the bridge was occurrence of corrosion stains at the expansion and welded connection joints. The expansion joints are poorly detailed and failed to operate as intended. As a result, significant corrosion occurred at these joints which lead to peeling of the paint and rust bleeding causing stains to form on the parapets, as shown in Figure 4.

An additional railing failure that was observed at the bridge was due to poor expansion joint and railing details that allowed penetration and accumulation of water inside the railing elements. Freezing and expansion of entrapped water inside the railing members during the winter months caused excessive tensile stresses to form inside the railing members leading to stretching and bulging of the walls of the tube structure. This lead to major structural damage to the railing (elongation and rupture of the walls) and destruction of the coating layers in the local areas. As a result, additional corrosion was initiated in these local areas due to the failure of the coating. These problems were observed in several sections of the railings along the length of the bridge, see Figure 5.

Figure 4: Baraboo Bridge Railing Connection/Expansion Joint

Figure 5: Baraboo Bridge Railing Damage Due to Freezing

3.4.2 Sauk City Bridge

The Sauk City Bridge (B-56-217) is located in Sauk County, Wisconsin, on US Highway 12 crossing the Wisconsin River. This bridge was constructed in 2002.The Sauk City bridge received decorative railings with a three-coat zinc-rich system that included a black color top-coat. Similar to the Baraboo Bridge, this bridge had problems with the coating system and structural details. The color fading on this bridge is relatively uniform and less prominent. The underside of the railing, with less sun exposure, did not exhibit excessive fading or loss of gloss in comparison with the other areas of the railings. These railings also had significant corrosion and rust bleeding at the expansion and connection joints, leading to formation of rust stains on the parapets. The rust stains are more noticeable on the white colored parapets for this Bridge.

Connection and expansion joints constructed in the railings of the bridge are shown in Figure 6. At both connection types, poor construction details were used and there were easy access points where water could penetrate and accumulate inside the tubular members of the railings. Due to insufficient drainage, accumulated water froze and expanded during the winter months that lead to excessive expansion and failure of both the tubular railing members and the coating system in the local areas, see Figure 7. It appeared that the WisDOT maintenance personnel or others attempted to remedy the water accumulation problem inside the railing members for this bridge after the initial construction by drilling small holes in some areas of the railings, see Figure 8. However, it was found that additional drainage were needed and most of the drilled holes were plugged with debris since they were small and located close to the base of the railing where debris tend to accumulate more frequently.

Figure 6: Sauk City Bridge Railing Connections

Figure 7: Sauk City Bridge Railing Damage Due to Freezing

Figure 8: Sauk City Bridge Railing Drainage Hole

3.4.3 Jefferson Bridge

The Jefferson Bridge (B-28-89) is located in Jefferson County, Wisconsin, on US Highway 18 crossing the Rock River. The bridge was constructed in 1998. The bridge received galvanized decorative railings with a black two-coat coating system applied over the galvanized steel. The research staff found uniform fading of the coating system throughout the length of the railings. They also observed fading and degradation of the top-coat in some areas directly on the top of the railings where the tie-coat was exposed, see Figure 9. It was also observed in some areas of the railings that the tie-coat peeled off from the galvanized steel, see Figure 10. It was also observed that the galvanization of the steel railing was effective and prevented steel corrosion and rust staining of the concrete parapets even though some coating failures were seen in the railings of this bridge.

Figure 9: Jefferson Bridge Railing Exposed Tie-Coat

Figure 10: Jefferson Bridge Loss of Adhesion in Railing Coating

Prior to the galvanization process of steel railings, holes are drilled in strategic locations of the railing to allow entrapped air or moisture to exit and to prevent bursting of the members due to expanding gases, see Figure 11. During the galvanization process the steel is submerged in a molten zinc bath at approximately 830°F. At these high temperatures, entrapped air and moisture will expand and form very high pressure if there is not adequate drainage or ventilation in the railing members. Drilling appropriate vent holes in the railing members is not only beneficial during the galvanization process, but also allows future water or moisture to drain from the inside of the railings. Because of adequate vent/drainage holes in the railing

members, there was no damage in the railing of this bridge due to water entrapment and freezing.

Figure 11: Jefferson Bridge Railing Galvanization Holes

3.4.4 Tomahawk Bridge

The Tomahawk Bridge (B-35-154) is located in Lincoln County, Wisconsin, on North 4th Street crossing the Wisconsin River. This bridge was constructed in 2011. The bridge received galvanized decorative railings with a black two-coat coating system applied over the galvanized steel. An enhanced structural detail used for the railing was based on eliminating the connecting members at the expansion joints, see Figure 12. In both galvanized and conventional railings these areas experience coating failures and corrosion more frequently due to the presence of moving members and sharp edges or discontinuities.

Figure 12: Tomahawk Bridge Railing Expansion Joint

3.4.5 Highland Ave and I-43 Bridge

The Highland Ave and I-43 Bridge (B-45-21) is located in Ozaukee County, Wisconsin, on Highland Ave crossing Interstate 43. This bridge was constructed in 2011. The bridge received galvanized decorative railings with a black two-coat coating system applied over the galvanized steel. The bridge railing contains vent holes cut at the base of each vertical member as shown in Figure 13. These vent holes were made to facilitate the galvanization process and prevent water or moisture from being trapped in the railings. It was observed that there are signs of corrosion particles in the vicinity of the vent holes, see Figure 14.

Figure 13: Highland Ave and I-43 Bridge Railing Vent Holes

Figure 14: Highland Ave and I-43 Bridge Railing Corrosion

It was found that several of these vent holes were unintentionally blocked during the galvanization process, see Figure 15. This could have led to entrapped moisture inside railings causing subsequent corrosion of the steel.

Figure 15: Highland Ave and I-43 Bridge Railing Blocked Vent Holes

3.4.6 Beloit Bridge

The Beloit Bridge (B-53-172) is located in Rock County, Wisconsin, on US Highway 81 crossing the Rock River. This bridge was constructed in 1996. The bridge received galvanized decorative railings with a green coating system applied over the galvanized steel. It was observed that there is fading of the coating system on this bridge and in some areas the coating system has been removed or degraded fully down to the galvanized steel, see Figure 16. The fading of the coating system is fairly uniform throughout the railings. The areas where the coating has been removed or degraded are mostly on the top part of the railing. Although these areas may be considered as being damaged by external mechanical sources, it is possible that the coating degradation is caused by a deposition of aggressive chemicals on the horizontal surfaces and the unblocked exposure to UV lights. Based on the review of available literature and preliminary test results by the research staff for this study, it can also be concluded that top-coats with lighter colors tend to degrade in shorter times when they receive the same level

of aggressive exposure as the darker color coatings. Again, it was observed that the galvanization of the steel railing was effective in preventing occurrence of corrosion even though the coating system has shown signs of failure at different areas of the railing at this bridge site. No mechanical connections or expansion joints are used in the railings of this bridge as adjacent sections of the railing are interrupted by short concrete pedestals rising from the top of the parapet supporting the railings, see figure 17. Also, there was no evidence of peeling of the coating from the galvanized steel in the railing of this bridge. Overall, it was concluded that the choice of appropriate structural details, coating system, and application has largely contributed to the relatively successful performance of the railings in this bridge for more than 15 years.

Figure 16: Beloit Bridge Railing Galvanized Railing

Figure 17: Beloit Bridge Railing Connections

4.0 Experimental Program

4.1 Introduction

An experimental program was carried out in this study to evaluate the performance of a selected number of coating systems for steel railing applications. The program included conducting accelerated weathering and UV exposure tests in addition to evaluations of key aesthetic and durability parameters influencing the overall performance of such coating systems.The experimental program was designed to simulate the most detrimental effects of natural weathering on coatings, to the extent possible, in laboratory and during a manageable time duration.

4.2 Accelerated Testing

Accelerated weathering tests can considerably reduce the time needed to evaluate the performance of coating systems, particularly if a comparative study is performed to assess performance of multiple coating systems that are subjected to the same exposure conditions. If appropriate test methods are selected and if they are performed properly, accelerated weathering tests can yield results in a reasonable time span that will be helpful to bridge owners in selecting and applying coating systems to bridge railing structures to achieve successful performance. It must be noted that no accelerated weathering or exposure test can fully duplicate true exposures to the real weather and field conditions but it can yield valuable results in the absence of those from real conditions that may be time intensive and more expensive.

4.2.1 Accelerated Weathering Apparatuses

For this study, three different accelerated weathering chambers were used to evaluate the selected coating systems. All three chambers were manufactured by Q-Lab Corporation. The first chamber, the QUV/se, was used to simulate the damaging effects of UV light on coated samples, see Figure 18. This chamber is able to produce UV light at predetermined irradiance

and temperature values, and to produce condensation at a set temperature. UV radiations have shorter wave lengths than visible light and as such have more radiant energy. Within the sunlight spectrum, the UV radiations have greater damaging effects on the durability of the coating materials compared with visible light.

The second chamber is used to simulate the damaging effects of salts (chlorides) on a coating system. The chamber is the Q-Fog Cyclic Corrosion Tester, Model CCT 600 as shown in Figure 19. This chamber can produce salt/fog at predetermined temperature and flow rate values.

To consider the effects of the full sunlight spectrum, or the longer wave-length radiations, on coating systems the experimental program included tests in the Q-Sun Xenon Arc Chamber, Model Xe-1-S, see Figure 20. This chamber is able to produce xenon light at predetermined irradiance and temperature values with and without spraying water options on the test specimens.

Figure 18: QUV/se, UV Testing Equipment

Figure 19: Q-Fog, Salt/Fog Testing Equipment

Figure 20: Q-Sun, Xenon Arc Testing Equipment

4.2.1.1 Water Purification

A de-ionized water purification system was required and used for operating the QUV, Q-Fog, and Xenon arc chambers. The water purification system in this experimental program exceeds all requirements of ASTM and manufacturer. The system includes a 10-inch carbon filter, a strong base set (two tanks), two mixed bed deionizer tanks, and re-circulating pump, as shown in Figure 21. The all-time resistivity of the purified water met the required minimum value of 10 MΩ-cm and on average it was around 14 MΩ-cm.

Water purifications resistivity requirement per ASTM D6695 for water spray in the Xenon Arc test equipment is a minimum of 0.2 MΩ-cm, but the manufacturer requirement for the Q-Sun test equipment is 10 MΩ-cm(32). Water requirement for the UV test equipment per

ASTM D5894 is that only de-ionized water must be used for condensation(31). Water purification resistivity requirement for Salt/Fog test equipment per ASTM D5894 is a minimum of 0.2 MΩ-cm.

Figure 21: Water Purification System and Mega Ohm Meter

4.2.2 Testing Program and Procedure

Selected coating systems were applied on steel test coupons and cured according to the manufacturers' recommendations. These samples were subjected to two separate accelerated tests. The first test is a modified version of ASTM Standard D5894-10: “Standard Practice for Cyclic Salt Fog/UV Exposure of Painted Metal” (31). This test is chosen to assess the overall effectiveness and durability of the coating systems. In this test, samples were subjected to alternating cycles of Freeze, UV exposure, and Salt/Fog exposure. The only modification to ASTM Standard D5894-10 is the addition of a freeze cycle. This test is referred to as the Freeze/UV/Prohesion test.

The second and separate test follows ASTM Standard D6695-08: “Standard Practice for Xenon-Arc Exposures of Paint and Related Coatings” (32). In Xenon-Arc testing, coated samples are subjected to the full sunlight spectrum instead of only the UV radiations. As longer wave

length radiations within the full sunlight spectrum primarily affect the color retention or fading of coating systems (normally only the top-coat), the Xenon Arc test is performed to assess this characteristic property of the coating systems included in this study. For this test, the samples were subjected to cycles of Xenon-Arc light and water spray. There were 12 coating systems selected for the Freeze/UV/Prohesion testing and 10 coating systems selected for the xenon arc test. Since only top-coats in coating systems are subjected to Xenon Arc tests, fewer test samples were used for this test due to a duplication of the same top-coats among different systems selected for this study. Table 1 lists the types and number of coating systems that were selected and used for each test.

Table 1: Coating System and Testing Program

Steel Coating Systems (New Application)	# of Coating Material Systems	# of Samples for Freeze/ UV/ Prohesion Tests 3"x6"	# of Samples for Freeze/ UV/ Prohesion Tests 4"x6"	# of Samples for Xenon[1] Testing 2"x2"
Three-Coat Polyurethane	3	15	6	3
Three-Coat Fluoropolymer	2	10	4	6
Duplex Liquid	3	15	6	9
Duplex Powder Coat	2	10	4	6
Two-Coat	2	10	4	6
Totals Systems	12	60	24	30

[1]Samples for Xenon tested in black and blue

4.2.2.1 Test Samples

Coated samples for ASTM Standard D5894 (Freeze/UV/Prohesion testing) testing were made in two different sizes under this study. The majority of the samples were 3 in. x 6 in. x 1/8 in. thick that were made of grade A36 steel. Additional samples made of light gage galvanized

sheets (24 gage or 0.024 in. thick) and conventional rolled steel sheets (22 gage or 0.030 in. thick) were made in size 4 in. x 6 in. and were used for duplex and conventional coating systems, respectively. These coated samples were used for measuring the flexibility of the coatings before and after the weathering tests through the use of Mandrel bend testing device.

To achieve a more uniform UV exposure on the coated samples, a smaller exposure window was used. The exposure windows, shown in Figure 22, for the 4 in. x 6in. and 3 in. x 6 in. samples were approximately 3.5 in. x 3.75 in. and 2.25 in. x 3.75 in., respectively.

When conducting ASTM Standard D6695 (Xenon Arc) test, Grade A36 steel samples with dimensions of 2 in. x 2 in. x 1/8 in. thick were used. No reduction of the exposed areas was required for this test.

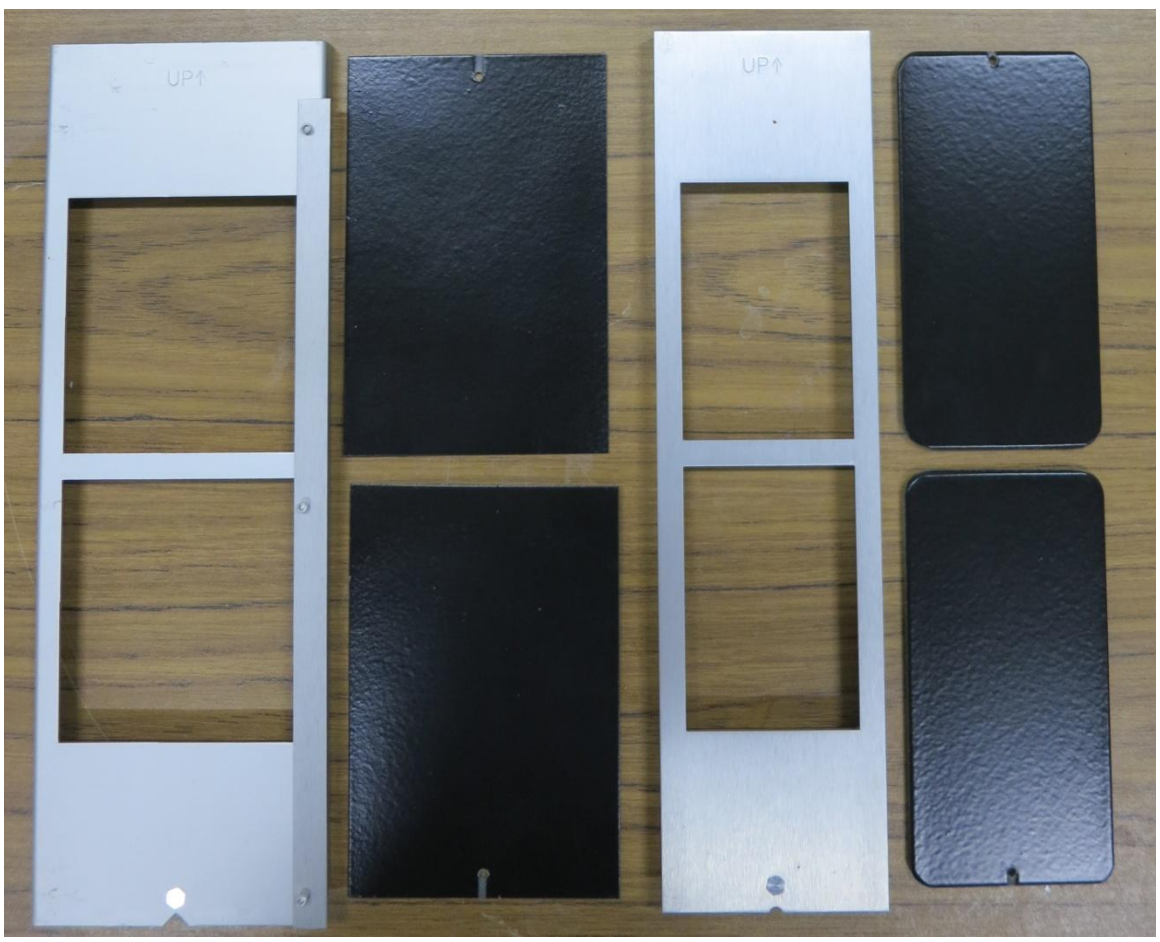


Figure 22: Exposure Windows for 4 in. x 6in. and 3 in. x 6 in. Samples

For the 1/8 in. thick samples, all cut edges and corners were rounded, see Figures 23 and 24. A hole was drilled in one end of each sample for handling during painting application. The light gage galvanized and non-galvanized samples were used as cut and only a hole was drilled at one end for handling during painting application, see Figure 25.

Figure 23: 3 in. x 6 in. Samples

Figure 24: 2 in. x 2 in. Samples

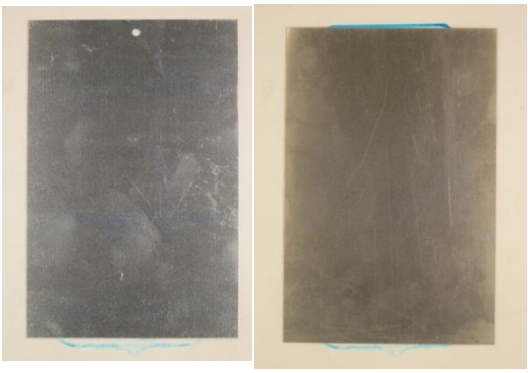


Figure 25: 4 in. x 6 in. Samples (Left: Galvanized, Right: Cold Rolled)

4.2.2.2 Freeze/UV/Prohesion

The accelerated weathering exposure tests for coated samples in this program was implemented by integrating an additional freezing cycle into the test under ASTM Standard D5894-10: "Standard Practice for Cyclic Salt Fog/UV Exposure of Painted Metal" (31). ASTM D5894 requires alternating weekly cycles of exposures in a Fog/Dry chamber and a UV/Condensation chamber. The modified test under this study incorporated a 24-hour Freeze cycle into the UV and Salt/Fog exposures. The addition of a freeze cycle to the testing program was intended to create physical/mechanical stresses in the coating due to drastic temperature changes. It was decided that the integration of the freeze cycle in the test program could better simulate the field conditions for assessing coating performance in Wisconsin climate Incorporating a freeze cycle into the ASTM D5894 test has also been shown by others to yield results that are closer to those obtained under field conditions (36).

ASTM D5894 test requires coated test panels be subjected to a minimum of 1008 hours of exposure or until a significant change can be observed in the performance related properties of the samples. Under this study, all coated samples were tested according to the modified ASTM D5894 standard for 15 cycles (5400 hours). Each cycle included full exposure for 15 days or 360 hours. Each cycle of exposure consisted of 24 hours in a Freeze chamber, 1 week (168 hours) in the UV light chamber, and 1 week (168 hours) in the Salt/Fog chamber. A Detailed exposure description during each cycle is shown in Table 2.

Table 2: Freeze/UV/Prohesion Test Cycle Summary

One cycle equals 360 total hours

1. Freeze: 24 hours
    - Temperature at -10°F (-23°C)
2. UV/Condensation: 168 hours (7 days)
    - Alternating Cycles of
        - 4 hours UVA-340nm with irradiance 0.89 W/m^{2}nm @ 140°F (60°C)
        - 4 hours condensation @ 104°F (40°C)
3. Prohesion (Salt/Fog): 168 hours (7 days)
    - Alternating Cycles of
        - 1 hour salt fog @ ambient temperature
            - Solution a mixture of 0.35% ammonium sulfate and 0.05% sodium chloride
        - 1 hour dry cycle, chamber is purged @ 95°F (35°C)

This study included performance evaluation for a total of 12 coating systems for new steel application using the modified Freeze/UV/Prohesion testing (ASTM D5895). For each coating system, seven 3 in. x 6 in. and four 4 in. x 6 in. samples were prepared and used in the testing program. From each group of seven 3 in. x 6 in. samples, two were kept as control specimens, and the remaining five were subjected to Freeze/UV/Prohesion test cycles. These five samples were tested with two having been scribed to test for rust creepage, and three were without scribing to assess changes in color and gloss.

The 4 in. x 6 in. samples were used for measuring the flexibility of the coatings. No scribing was made on these samples. Two samples were designated as control samples and the remaining two samples were subjected to Freeze/UV/Prohesion test cycles. Tables 3 and 4 show the number of samples tested for each coating system and the total number for all coating systems that were tested under Freeze/UV/Prohesion conditions. All 3 in. x 6 in. and 4 in. x 6 in. samples had a top-coat in color black with federal color code 27038.

Table 3: Samples per Coating System Tested Under Freeze/UV/Prohesion

Scribed 3 in. x 6 in.	Un-Scribed 3 in. x 6 in.	Control 3 in. x 6 in.	Un-Scribed 4 in. x 6 in.	Control 4 in. x 6 in.	Total Samples Per Coating System
2	3	2	2	2	11

Table 4: Total Samples Tested Under Freeze/UV/Prohesion

Total Number of Coating Systems	Number of Samples Per Coating System	Total Number of Samples
12	11	132

Ammonium Sulfate and sodium chloride from Acros Organics were used in testing for this study. According to ASTM D5894 standard, the total impurities of both the sodium chloride and the ammonium sulfate must be less than 0.3% by weight. The certificate of analysis for Ammonium sulfate (lot # A0299195) had an assay of 100.5% and for sodium chloride (lot# A0301750) the assay was 99.8%. Both the sodium chloride and ammonium sulfate were within the required permitted range for total impurities.

ASTM Standard D5894 requires the Salt/Fog chamber to have a uniform spray throughout the chamber space with a flow rate of 1-2 ml/hour. This is required to make certain that all coated samples inside the chamber are exposed to the same level of salt fog during each test cycle. To verify the uniformity of the spray and its flow rate, six graduated cylinders with funnels were placed at different locations inside the chamber, see Figure 26. The chamber was operated for a 16-hour fog cycle using the mixed solutions and the collected solution in each of the graduated cylinders was measured. The spray nozzle in the chamber was adjusted as needed to arrive at the required solution spray rate as well as a uniform spread of the solution throughout the chamber. These were verified by repeating the operation of the chamber for 16 hours and making a new set of measurements for the collected solution in the graduated cylinders. The pH of the solution collected in the graduated cylinders was measured at an

average value of 5.16 where it was verified that it was within the required range of 5.0 to 5.4. These measurements and verifications were made to meet the necessary calibration requirements of ASTM D5894 prior to the start of any testing using the Salt/Fog chamber. Table 5 shows the locations of the graduated cylinders and the measured solution volumes after the final calibration exercise of the chamber.

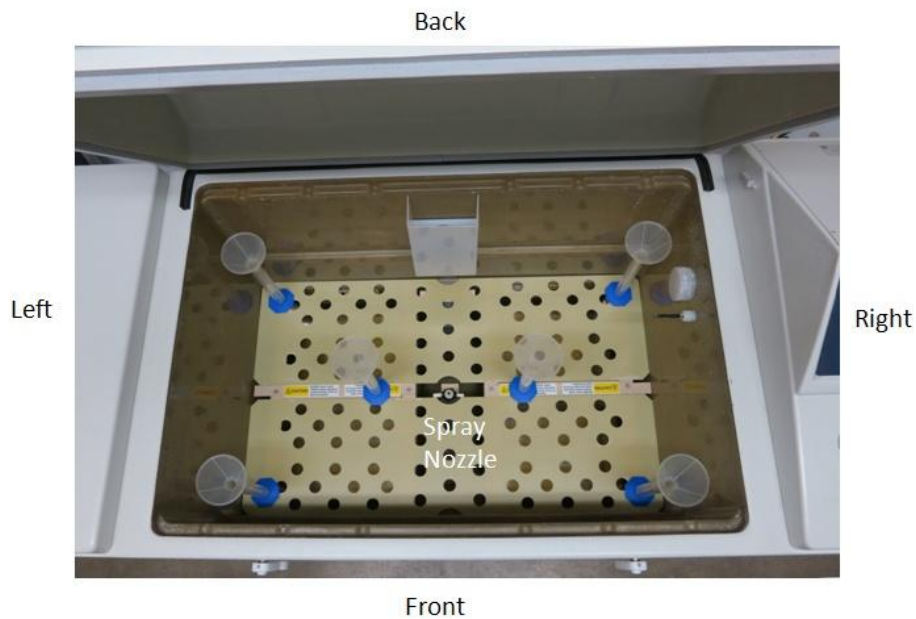


Figure 26: Placement of Graduated Cylinders for Calibration

Table 5: Measured Solution after 16 Hour Calibration

Back

	Volume (ml) 26				Volume (ml) 29	
Left		Volume (ml) 19	Spray Nozzle	Volume (ml) 23		Right
	Volume (ml) 22				Volume (ml) 22	

Front

4.2.2.3 Xenon Arc Testing

Xenon Arc testing, ASTM G155: "Standard Practice for Operating Xenon Arc Light Exposure of Non-Metallic Materials," was conducted to evaluate changes that occur in the color and gloss of top-coats in the coating systems for this study. The changes are primarily due to the combined effects of exposure to both short and long wave radiations within the sunlight spectrum. In addition, this test was performed to determine the effect of top-coat color (black vs. blue) on changes in color and gloss of the coated samples. The Xenon Arc test was conducted for 15 weekly cycles (2,520 hours) for all top-coats that were included in the study. One cycle of Xenon Arc test consists of one week (168 hours) of exposure in the Xenon Arc chamber that included repeating cycles of 102 minutes of Xenon light and 18 minutes of Xenon light combined with water spray. A detailed description of the repeating cycles of dry and wet Xenon light exposure is shown in Table 6.

Table 6: Xenon Arc Testing Summary

One cycle equals 168 total hours

1. Xenon light: 102 minutes
    a. Irradiance: 0.35 W/m^2nm
    b. Temperature: 145°F (63° C)
2. Xenon light combined with water spray: 18 minutes at ambient temperature

Three coated samples of 2 in. x 2 in. x 1/8 in. thick were prepared for each coating system and tested in the Xenon Arc chamber. Only 10 of the 12 coating systems were selected for the Xenon Arc testing in this study. The reduction in the number of test samples was made since there were duplications of top-coats among the duplex and 3-coat polyurethane coating systems that were included in the study. Table 7 shows the number of all coating systems in the

study and the number of test samples used for the Xenon Arc test. A 15-week cycle of the Xenon Arc test was performed for the selected samples in top-coat color of black (federal code 27038) and it was repeated for top-coat color of blue (federal code 15092).

Table 7: Xenon Arc Testing

System Type and #	Number of Systems	# of 2x2x1/8 in Samples for Xenon Testing[1] (ASTM G155)
3-Coat Polyurethane (PPG-3P)	1[2]	3[2]
3-Coat Fluoropolymer (CB-3F, SW-3F)	2	6
2-Coat (CB-2, PPG-2)	2	6
Duplex Paint (SW-D, CB-D[3], WA-D)	3	9
Duplex Powder Coat (SW-04PD, SW-05PD)	2	6
Total	10	30

[1] Samples tested in federal color (27038) black and federal color (15092) blue

[2] Only PPG-3P was used in the test since top-coats are the same for coating SW-D/SW-3P and for CB-D/CB-3P

[3] CB-3P was selected for Xenon Arc test of blue color

4.2.3 Measured Test and Evaluation Parameters

The following test and evaluation parameters were used according to ASTM standards to assess the performance of all coating systems that were subjected to accelerated weathering exposures under this study:

- **Gloss Retention** - ASTM D523-05: "Standard Test Method for Specular Gloss"
- **Color Retention** - ASTM D2244-09a: "Standard Practice for Calculation of Color Tolerances and Color Differences from Instrumentally Measured Color Coordinates"
- **Rust Creepage** - ASTM D7087-05a: "Standard Test Method for an Imaging Technique to Measure Rust Creepage at Scribe on Coated Test Panels Subject to Corrosive Environments"

- **Coating Defects or Holidays** - ASTM D5162-08: "Standard Practice for Discontinuity (Holiday) Testing of Nonconductive Coatings on Metallic Substrates"
- **Dry Film Thickness** - ASTM E376-06: "Standard Practice for Measuring Coating Thickness by Magnetic Field or Eddy Current (Electromagnetic) Examination Methods"
- **Pencil Scratch Hardness** - ASTM D3363-05: "Standard Test Method for Film Hardness by Pencil Test"
- **Adhesion** - ASTM D4541-09: "Standard Test Method for Pull Off Strength of Coatings Using Portable Adhesion Testers"
- **Flexibility** - ASTM D522-93a (Re-Approved 2008): "Mandrel Bend Test of Attached Organic Coatings"
- **Degree of Blistering** - ASTM D714-09: "Test Method of Evaluating Degree of Blistering"
- **Degree of Rusting** - ASTM D610-08: "Test Method of Evaluating Degree of Rusting"

4.2.3.1 Test and Evaluation Parameters for Freeze/UV/Prohesion Exposure

An evaluation of some of the coated panels was made after completion of every 15-day cycle (360 hours) of freeze/UV/prohesion exposure. After each cycle, two scribed 3 in. x 6 in. panels for each coating system were evaluated for rust creepage at the scribed locations, degree of rusting, and degree of blistering. The three remaining un-scribed panels for each coating system were evaluated for changes in color and gloss, degree of rusting, and degree of blistering and holidays. The adhesion and pencil hardness tests were performed on control samples for each coating system prior to the start of the accelerated weathering tests and the tests were performed on all weathered panels after the completion of the weathering tests. The flexibility test for each coating system was performed initially on the control 4 in. x 6 in. panels and again on the weathered panels after the completion of the weathering tests. Table 8 shows all

evaluation tests that were performed on coated samples that were subjected to Freeze/UV/Prohesion testing.

Table 8: Evaluation Tests Freeze/UV/Prohesion

Evaluation Tests	Scribed 3 x 6 in.	Un-Scribed 3 x 6 in.	Un-Scribed 4 x 6 in.
Gloss Retention - ASTM D523-05		x[1]	
Color Retention - ASTM D2244-09a		x[1]	
Rust Creepage - ASTM D7087-05a	x[1]		
Coating Defects or Holidays - ASTM D5162-08	x[1]	x[1]	
Dry Film Thickness - ASTM E376-06		x[1]	
Degree of Blistering - ASTM D714-09	x[1]	x[1]	
Degree of Rusting - ASTM D610-08	x[1]	x[1]	
Adhesion - ASTM D4541-09	x[2]	x[2]	
Pencil Scratch Hardness - ASTM D3363-05		x[2]	
Flexibility – ASTM D522-93a			x[2]

[1] Tests performed each cycle

[2] Tests performed on control samples and at completion of testing program

4.2.3.2 Test and Evaluation Parameters for Xenon Arc Exposure

All coated samples were tested for initial color, gloss, and dry film thicknesses prior to the start of the Xenon Arc testing. After each weekly cycle of exposure, the samples were evaluated for changes in color, gloss, and dry film thickness. Table 9 shows all evaluation tests that were performed on coated samples that were included in the Xenon Arc test.

Table 9: Evaluation Tests Xenon Arc

Evaluation Tests Per Cycle	2 in. x 2 in.
Gloss Retention - ASTM D523-05	x
Color Retention - ASTM D2244-09a	x
Dry Film Thickness - ASTM E376-06	x

4.2.3.3 Color Retention and Gloss Retention

Changes in gloss for coated samples in this study were measured based on ASTM D523-05: “Standard Test Method for Specular Gloss” was followed (37). Change in color were measured based on ASTM D2244-09a: “Standard Practice for Calculation of Color Tolerances and Color Differences from Instrumentally Measured Color Coordinates” was used (38). Both gloss and color readings where measured using a BYK Gardner Spectro-Guide Sphere device, shown in Figure 27.

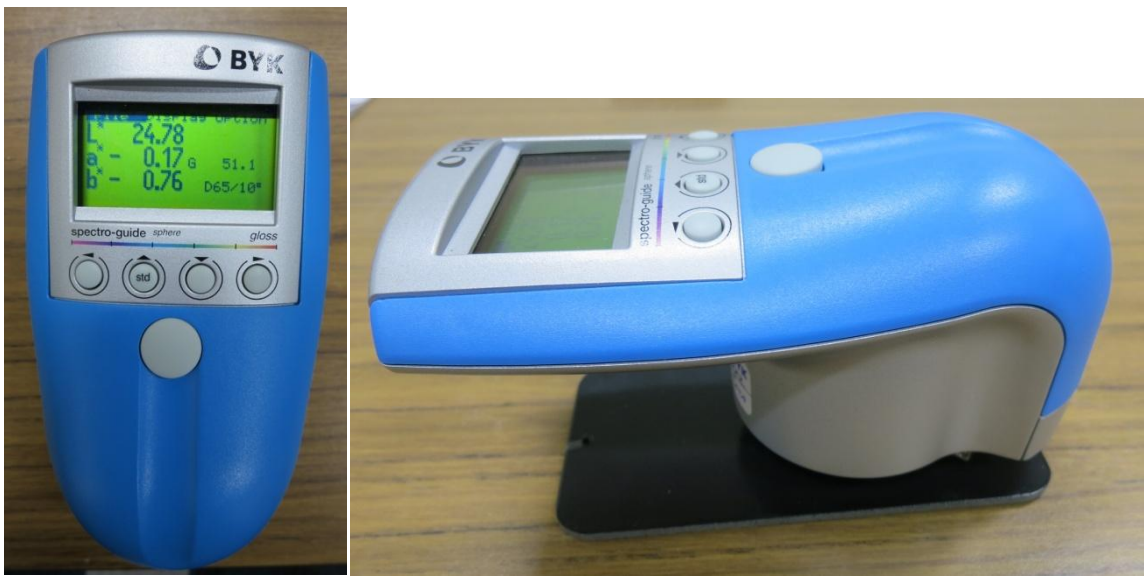


Figure 27: BYK Spectro-Guide

Gloss is measured in terms of a surface being able to reflect a certain level of light. The more light a surface can reflect the larger the gloss index or a "G" value as measured by the BYK Spectro-Guide device. The measurement of the gloss index is made at a 60° angle. The average value of six measurements on each 3 in. x 6 in. panel was taken as the gloss index value for that panel. Three measurements were taken diagonally across the top and bottom surfaces of the

exposure area of each panel. For the 2 in. x 2 in. samples, three measurements were taken near the center and an average value was obtained to represent that panel's gloss index.

To assess changes in the colors of the coated samples subjected to accelerated weathering test, the CIELAB color indexing model or standard was used in this study. The standard was adopted by the "Commission Internationale de l'Eclairage" or "International Commission on Illumination" (CIE) in 1976. The CIELAB system is a mathematical representation of the color in space and it is based on the perception of color by people. Three variables of "L", "a", and "b" are used to indicate the level or range of lightness (where black = 0 and white = 100), green to red (where green = -a and red = +a), and blue to yellow (where blue = -b and yellow = +b), respectively.

The L, a, and b values for each coating system were recorded initially on control coated panels and after each cycle of weathering exposure during this study. The BYK Spectro-Guide device was used to measure the L, a, and b variables. Similar to the measurement of the gloss index values as described earlier, six color measurements were taken for the 3 in. x 6 in. panels and three measurements for 2 in. x 2 in. samples .

Under the CIELAB model, the difference in color is measured by ΔE where $\Delta E=\sqrt{(\Delta L)^2+(\Delta a)^2+(\Delta b)^2}$. The parameters ΔL, Δa, and Δb are defined as differences between two subsequent measurements for L, a, and b, respectively. In this study, ΔE was calculated for each coating system by using the measured values of L, a, and b from the control panels and those from weathered panels after each cycle of accelerated weathering test. Since color black was used for coated samples in the accelerated weathering test, the changes in lightness, or ΔL, was determined and evaluated after each test cycle.

4.2.3.4 Rust Creepage

Rust creepage at each scribe on coated panels was measured and evaluated based on ASTM D7087-05a: "Standard Test Method for an Imaging Technique to Measure Rust Creepage at Scribe on Coated Test Panels Subject to Corrosive Environments" (39). Panels were first scribed using a lathe bit and the scribing apparatus shown in Figure 28. The scribing tool was used to ensure all scribes were created the same way. Only the 3 in. x 6 in. coated panels were scribed in this study and each scribe was located within the UV exposure area of the panel. After scribing the samples, they were subjected to the accelerating weathering test cycles.

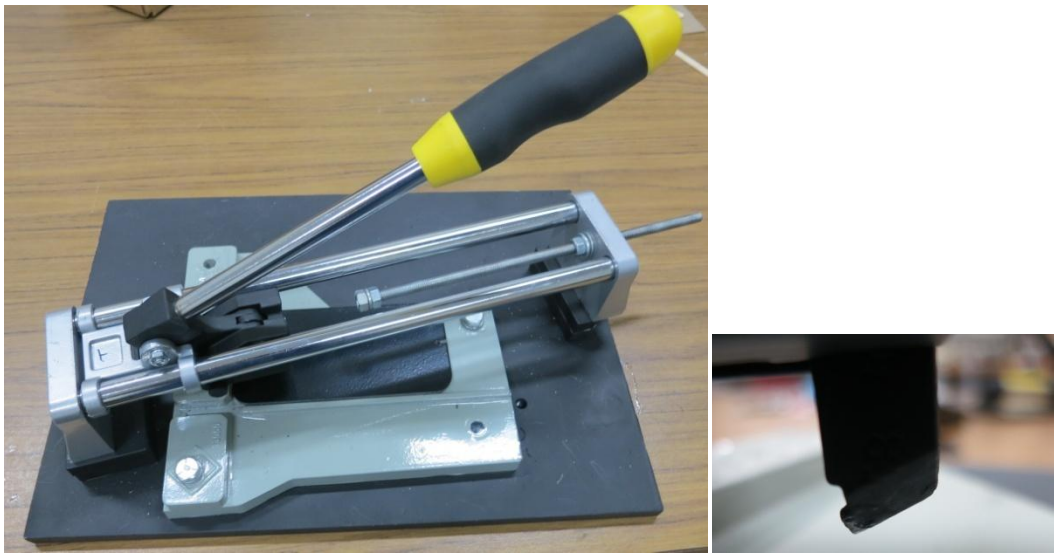


Figure 28: Scribing Tool

According to the ASTM standard, the original scribe length and widths were recorded and the rust creepage was measured and recorded after each accelerated weathering test cycle. The scribe length for all coated panels was 2.0 in. and the scribe width for most panels was 0.02 in. The scribe width for SW-3-P panel 2 and PPG-2 panel 3 was 0.031 in., and for SW-3-P and PPG-2 panel 3 was 0.024 in.

To measure the rust creepage, a transparent film (3M model AF4300) was placed over the scribed area and the rust creepage was outlined on it. Points on the transparent film were marked as shown in Figure 29. Points g and h represent a distance that is 80% of the original scribed length. The transparent film was scanned and used in Adobe Photoshop imaging software to calculate the area of the rust creepage. The imaging software uses a mathematical integration technique to calculate the area. Using the integrated area, the mean creepage and net mean creepage were calculated using the following equations.

- Mean Creepage: $C = A_{ijlk}/2L$
  - C = Mean creepage in mm
  - A_{ijlk} = Integrated area inside the boundary of (ijkl), shown in Figure 29
  - L = Length of the scribe line from which creepage is extended and area is integrated
- Net Mean Creepage: $C_{net} = A_{ijlk} - A_O/2L$
  - C_{net} = Net mean creepage in mm
  - A_{ijlk} = Integrated area inside the boundary of (ijkl), shown in Figure 29
  - A_O = Integrated area of scribe line before exposure
  - L = Length of the scribe line from which creepage is extended and area is integrated

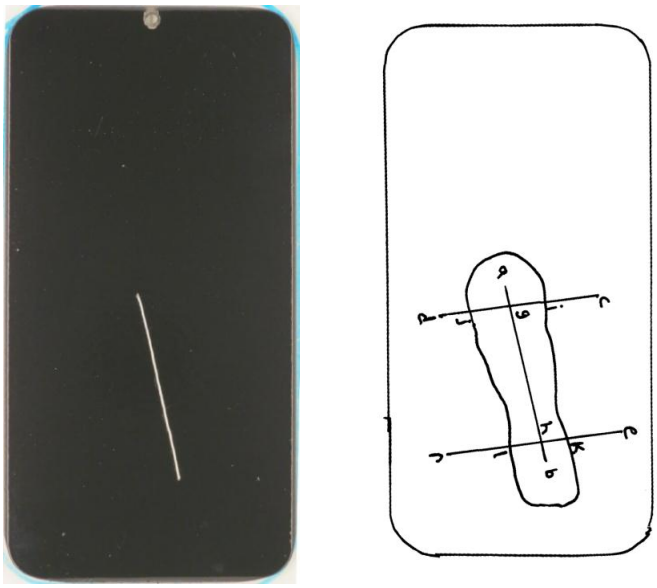


Figure 29: Scribe Sample and Rust Creepage Traced Image

4.2.3.5 Coating Defects or Holidays

Holidays in the coating systems for this study were measured initially and at the end of each cycle according to ASTM D5162-08: “Standard Practice for Discontinuity (Holiday) Testing of Nonconductive Coatings on Metallic Substrates” (41). A low voltage wet sponge tester was used to detect voids that penetrate the coating down to the steel substrate, see Figure 30. The Holidays detection test was conducted for both the control panels, before the start of the accelerated weathering exposure, and after each test cycle for the panels that were subjected to the weathering test. The set voltage was 90 volts for this wet sponge detector.

Figure 30: Wet Sponge Detector

The wet sponge detector consists of a voltage detector or meter, a wet detecting sponge using de-ionized water, and a return ground wire connected to the sample. The return ground is attached to a clamp that penetrates the coating down to the substrate on the back side of the test sample. If a defect or holiday is detected, the device will create a closed circuit and sound an alarm. The locations of all detected holidays for the coating systems in this this study were marked on the panel and recorded for each test.

4.2.3.6 Dry Film Thickness (DFT)

The dry film thickness values for the coating systems in the study were measured according to ASTM E376-06: “Standard Practice for Measuring Coating Thickness by Magnetic Field or Eddy Current (Electromagnetic) Examination Methods” (42). These measurements were taken using the BYKO-Test MPOR eddy current gage, shown in Figure 31.

Figure 31: Dry Film Thickness Gage

Eddy current devices can measure variations in the impedance of an eddy current inducing coil caused by coating thickness variations (43). Six measurements of dry film thickness measurements were taken on the 3 in. x 6 in. test samples. Dry film thickness measurements were made for both the control panels, before the start of the accelerated weathering exposure, and after each weathering cycle for panels that were subjected to the weathering test. Three measurements were taken on the top portion and three measurements were taken on the bottom portion of the exposure area of each coated panel. The average value of the readings for each coated panel was recorded as the dry film thickness for that panel. For the 2 in. x 2 in. samples, three measurements were taken around the center area of each sample.

4.2.3.7 Pencil Scratch Hardness

Pencil scratch hardness for coated samples in this study was measured according to ASTM D3363-05: “Standard Test Method for Film Hardness by Pencil Test” (44). A BYK pencil harness tester, shown in Figure 32, was used to perform this test. This testing device allows for a uniform pressure to be applied to the surface of a coated sample with a pencil of sufficient hardness that is held at a 45° angel to the sample (45). The appropriate hardness of the pencil lead is determined by trial and error where multiple pencils with varying lead hardness levels

are used until a pencil with the hardest lead that cannot scratch the coating is found. Prior to each test, the tip of the pencil lead is required to be flattened with a No. 400 grit abrasive to achieve a flat, smooth, and circular cross section.

Figure 32: Pencil Hardness Tester

This test is used to determine the hardness or scratch resistance of a coating. For each coating system in the study, the pencil hardness and scratch hardness tests were initially conducted on two 3 in. x 6 in. coated control samples and then on three un-scribed 3 in. x 6 in. samples at the completion of the accelerated weathering tests.

4.2.3.8 Adhesion

Adhesion strengths of coating films to the substrate were measured on 3 in. x 6 in. coated panels for all coating systems in the study according to ASTM D4541-09: "Standard Test Method for Pull Off Strength of Coatings Using Portable Adhesion Testers" (46). A PosiTest manual adhesion tester with 0.79 in. diameter dollies, as shown in Figure 34, was used for measuring the adhesion strength of the coating systems. Two control samples per coating system were tested for adhesion prior to the start of the accelerated weathering test. Three un-scribed and the two scribed 3 in. x 6 in. samples were tested for their adhesion strength after the completion of the weathering test. For each coated panel, three adhesion strength

measurements were made with one measurement at the top, middle and bottom of the exposure window.

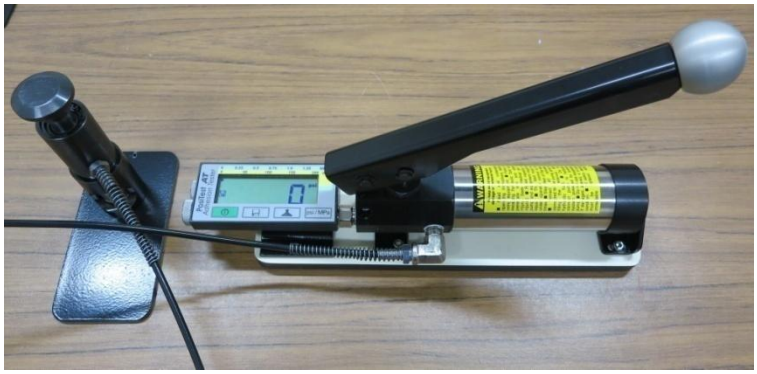


Figure 33: Adhesion Tester

A synthetic steel wool pad was used to clean the testing dollies prior to each test. A two part epoxy adhesive was used to secure each dolly to a coated panel. Any excess adhesion was removed from around the dolly after its installation on the panel. The preparation and installation process for the dollies is shown in Figure 34. The epoxy adhesive was allowed to dry for a minimum of 24 hours. Each installed dolly was then pulled from the surface of the panel using the manual adhesion tester. The test was conducted at a load rate of approximately 150 psi/sec.

For each individual test, the greatest mean pull-off stress and type of failure was recorded. Failure types are classified as a cohesive failure, adhesive failure, or a combination of both. An adhesive failure occurs between the interface of two coating layers. A cohesion failure occurs within a single coating layer. For each test, the percentages of adhesive and cohesive failures in accordance to their respective areas and locations within the coating layers are recorded.

Figure 34: Adhesion Test Preparations

4.2.3.9 Coating Flexibility

Coating flexibility for coating systems in the study was measured according to ASTM D522-93a (Re-Approved 2008): "Mandrel Bend Test of Attached Organic Coatings" (47). A conical Mandrel Tester, as shown in Figure 35, with a cone-shaped mandrel ranging from a diameter of 0.125 in. at one end to 1.5 in. at the other end was used to perform this test. This test was performed on 22 gage cold rolled and 24 gage galvanized 4 in. x 6 in. test samples. The samples are secured in the Mandrel Tester and then the lever is moved 180° at a uniform velocity and force. Each test takes approximately 15 seconds. After conducting a test, the bent sample is examined for the extent and size of any cracks formed in the coating due to the bending process. Each crack length is measured and it is assumed that all cracks are extended to the small end of the Mandrel. The percent elongation is also calculated according to the ASTM standard. Adjustments were made to the measured values for coatings with thickness more than 1 mil or 0.001 in.

Figure 35: Conical Mandrel Tester

4.2.3.10 Degree of Blistering

Blistering of the selected coating systems were evaluated according to ASTM D714-09: "Test Method of Evaluating Degree of Blistering" (48). In the standard, blisters are classified by their size and frequency. Photographs of the reference samples are included in ASTM D714-09 and were used for determining the size and frequency of the blisters in the coating systems selected for this study.

The size of the blisters was determined by using a numerical scale with size No. 10 to 0, where size No. 10 representing no blisters, size No. 8 representing the smallest blisters that may be seen with the unaided eye, and blister sizes No. 6, 4, 2, and 0 representing progressively larger sizes. Frequency of the blisters is classified in four categories. These categories include: dense (D), medium dense (MD), medium (M), and few (F). As it can be concluded, the measuring of size and frequency for blisters in coating systems are made based on a qualitative approach.

4.2.3.11 Degree of Rusting

The extent of rusting for the selected coating systems in the study was evaluated according to ASTM D610-08: "Test Method of Evaluating Degree of Rusting" (49). A standardized approach to quantify the extent and frequency of visual surface rust in coatings is provided in

ASTM D610-08. The extent of rusting is evaluated on a 0 to 10 scale based on the percent of visual surface rust. The distribution or frequency of the surface rust in coatings is classified as spot rust (S), general rust (G), and pinpoint rust (P). Visual reference samples shown in ASTM D610-08 were used to determine the extent and frequency of the rusting in the coating systems in this study.

4.3 Coating Systems

Liquid and powder coating systems were selected for performance evaluation in this study. The selected liquid coating systems consisted of 3-coat, 2-coat, and liquid duplex (painting over galvanized steel) coating systems. The selected powder coating systems consisted only of duplex systems.

4.3.1 Conventional Liquid Coating Systems

Conventional liquid coating systems consist of one or more layers of individual coatings applied to a steel substrate. These coatings commonly are either 2- or 3-coat systems. Individual liquid coatings are typically made up of binders/resins, pigments, solvents, and additives (50).

4.3.1.1 Three-Coat Systems

Three-coat coating systems consist of a primer, intermediate coat, and a top-coat. The 3-coat coating systems selected in this study consisted of an organic zinc-rich primer, an epoxy mid-coat, and either a fluoropolymer or polyurethane top-coat.

Each coat in a coating system is selected and used to serve a specific function. The zinc primer acts as a sacrificial protection barrier against exposures to moisture and corrosion. Along with strong adhesion properties, the epoxy intermediate coat is used to primarily increase the total overall thickness of a coating that will offer additional mechanical protection. The fluoropolymer or polyurethane top-coat is used to gain resistance to the atmosphere and UV

light exposure. In addition, the top-coat is used to enhance the visual aesthetics of the structure that is coated with a coating system.

4.3.1.2 Two-Coat Systems

Two-coat coating systems consist of a primer and a top-coat. The 2-coat coating systems selected for this study consisted of an organic zinc-rich primer and a polysiloxane top-coat. The zinc primer and the top-coat serve the same functions as those in the 3-coat coating systems.

4.3.2 Duplex Coating System

A common duplex coating system consists of a galvanized steel substrate that is coated with a tie-coat and a top-coat. The selected duplex coating systems in this study included galvanized substrates with both a conventional sprayed liquid paint and with a powder coating process. A typical conventionally sprayed duplex coating system includes an epoxy tie-coat followed by a polyurethane top-coat.

The primary advantage of a duplex system is the protection of the steel against corrosion by the galvanized layer that is installed on the steel substrate. In the event of a failure of the tie-coat and top-coat, the galvanized steel will resist most aggressive environments against corrosion. For bridge handrails, the hot-dip galvanization process offers protection against corrosion for both outside and inside surfaces of the railing members. This allows for better protection of the railing in cases where moisture is able to penetrate the inside of the railing. The main disadvantage to galvanization is potential problems with long-term adhesion of the intermediate coating layer to the galvanized surface.

4.3.2.1 Duplex Liquid Coating

The selected duplex liquid coating systems in this study consisted of a tie-coat and a top-coat. The tie-coat is primarily used to form a strong bond to the galvanized substrate and also to allow for proper adhesion of the top-coat. In this study, three different types of tie-coats

were used and they included: urethane, epoxy, and a waterborne acrylic. The top-coat for the liquid duplex stems included urethane and polyurethanes.

4.3.2.2 Duplex Powder Coating

Similar to the liquid duplex coating systems, each selected powder coat duplex system in this study contained a tie-coat and a top-coat. The tie-coat consisted of an epoxy that was used to promote adhesion to the galvanized substrate and adhesion of the top-coat. There were two different types of top-coats that were used and evaluated in this study. These included a polyester top-coat and a fluoropolymer top-coat.

4.3.3 Selected Coating Systems

Table 10 lists detailed information for the twelve coating systems that were selected and included in this study. The information includes coating compositions, the corresponding manufacturers' recommended dry film thicknesses (DFT), and coating systems identification designations that are used to describe these systems throughout this report.

Table 10: Selected Coating Systems

3-Coat Polyurethane Systems

Coating ID.	Manufacturer	Primer /DFT(mils)	Intermediate Coat /DFT(mils)	Top-Coat /DFT(mils)
SW-3P	Sherwin Williams	Zinc Clad III /(3-6)	Macropoxy 646 /(3-10)	Acrolon 218 HS /(3-6)
CB-3P	Carboline	Carbozinc 859 /(3-5)	Carboguard 888 /(3-5)	Carbothane 133LH /(3-5)
PPG-3P	PPG	Amercoat 68HS /(3)	Amercoat 399 /(4-8)	Amercoat 450H /(2-5)

Table 11: Selected Coating Systems (Continued)

3-Coat Fluoropolymer Systems

Coating ID.	Manufacturer	Primer /DFT(mils)	Intermediate-Coat /DFT(mils)	Top-Coat /DFT(mils)
SW-3F	Sherwin Williams	Zinc Clad III /(3-6)	Macropoxy 646 /(3-10)	Fluorokem /(2.5-3)
CB-3F	Carboline	Carbozinc 859 /(3-5)	Carboguard 888 /(3-5)	Carboxane 950 /(2-3)

2-Coat Systems

Coating ID.	Manufacturer	1st Coat /DFT(mils)	2nd Coat /DFT(mils)
CB-2	Carboline	Carbozinc 859 /(5-7)	Carboxane 2000 /(7)
PPG-2	PPG	Amercoat 68HS /(3)	PSX 700 /(3-7)

Duplex Systems with Sprayed Liquid Coatings

Coating ID.	Manufacturer	Tie-Coat /DFT(mils)	Top-Coat /DFT(mils)
SW-D	Sherwin Williams	Macropoxy 646 /(2-4)	Acrolon 218 HS /(2-4)
CB-D	Carboline	Galoseal WB /(0.5-1)	Carbothane 133LH /(3-5)
WA-D	Wasser	MC-Ferrox B 100 /(3-5)	MC-Luster 100 /(2-4)

Duplex Systems with Powder Coatings

Coating ID.	Manufacturer	Tie-Coat /DFT(mils)	Top-Coat /DFT(mils)
SW-04PD	Sherwin Williams	EAS6-C000 Epoxy /(1.8-3)	AAMA 2604 Polyester /(2-3)
SW-05PD	Sherwin Williams	EAS6-C000 Epoxy /(1.8-3)	AAMA 2605 Fluoropolymer /(2-3)

4.4 Surface Preparation

Proper adhesion of a coating film to its substrate or other layers of coating is essential for effective and successful performance of a coating system. Surface preparation is one of the key factors for achieving proper adhesion. Depending on the type of substrate and coating application requirements, an appropriate surface preparation must be performed. Proper surface preparation for steel includes; removal of all mill scale, grease, dirt, and other contaminants before application of the first layer of coating. In addition, an adequate surface profile on the substrate is needed for proper adhesion. A smooth surface profile can negatively affect the adhesion of the coating to its substrate.

4.4.1 Liquid Coating Surface Preparation

All liquid coated non galvanized test panels in this study were prepared according to SSPC-10/NACE NO.2: “Near-White Blast Cleaning” (51). Prior to any sand blasting of the substrate, SSPC-10/NACE NO.2 requires that all surfaces must be cleaned and free from all visible deposits of oil, grease, and other contaminants, following SSPC -1: “Solvent cleaning” (52). Also, it requires that 95% of the surface must be free from all visible residues with only staining permitted on the remaining area. All samples in this study were cleaned with an Acetone Solvent prior to sandblasting. Samples were sand blasted per SSPC-10/NACE NO.2 the same day of the application of the zinc prime coat. Figure 36 shows samples before and immediately after they were sand blasted. After the sandblasting of the plates, they were subjected to high pressure air to remove any dust and debris from the surface. In addition, samples were inspected and cleaned per SSPC-1 to remove any visible remaining contaminants.

Figure 36: Sample Before and After Sandblasting

A sandblasting cabinet, shown in Figure 37, was used to blast the test plates. These plates were sandblasted at a 90 degree angle with a 90 psi pressure and using a 1/4 in. diameter carbide nozzle. Aluminum oxide (16 grit) was used as the sandblasting medium. Surface profile was measured on every sixth 3 in. x 6 in. panel to make certain that appropriate profile is achieved. Generally, manufacturers recommend achieving a surface profile between 1.5 and 2.5 mils for proper adhesion of a coating layer to steel substrates. Testex Press-O-Film tape and a micrometer were used to measure the surface profile as shown in Figure 38. For each reading, both Coarse and X-Coarse Testex tapes were used when measuring the surface profiles. This was done to follow the instructions by Testex for cases where the surface profile actually range between 1.5 and 2.5 mils which was the case for the measured surface profile for the test plates under this study. Table 11 lists the measured surface profile values as well as the average values that range between 2.0 and 2.3 mils.

Figure 37: Sandblasting Cabinet

Figure 38: Testex Tape and Micrometer

Table 12: Surface Profile Values

Profile Reading	Coarse Profile (mils)	X-Coarse Profile (mils)	Average
1	2.1	2.4	2.3
2	1.9	2.5	2.2
3	2.0	2.5	2.3
4	2.0	2.5	2.3
5	2.1	2.4	2.3
6	1.8	2.3	2.1
7	1.8	2.5	2.2
8	1.8	2.2	2.0
9	1.8	2.4	2.1
10	1.8	2.3	2.1
11	2.0	2.4	2.2
12	1.8	2.2	2.0
13	1.9	2.3	2.1
14	1.9	2.4	2.2

4.4.2 Duplex Surface Preparation

For duplex coating systems, appropriate surface preparation must be done prior to the galvanizing of the steel substrate as well as when the galvanization is completed.

4.4.2.1 Initial Surface Preparation before Galvanizing

The initial surface preparation for a steel substrate is provided in WisDOT's Special Provision for Galvanized railings. In this study, test plates were first cleaned by a solvent and were then sandblasted to remove most of the mill scale prior to being galvanized. The plates were sandblasted according to SSPC-6/NACE No. 4 “Commercial Blast Cleaning” prior to the galvanization process(23). Figure 39 shows two test plates with and without the sandblasting process.

Figure 39: Surface Preparation Prior to Galvanizing

Immediately after the sandblasting of the plates was completed, they were transferred to the facilities of ACME Galvanization in Milwaukee, WI where they were galvanized within a few hours. It was made certain that no water quenching or chromate treatment was applied to the galvanized plates by the galvanizer.

4.4.2.2 Final Surface Preparation prior to Application

After the completion of the galvanization, the plates were cleaned following the requirements of SSPC-1. The samples were then subjected to a brush-off blasting process according to SSPC-16 “Brush-Off Blast Cleaning of Coated and Uncoated Galvanized Steel, Stainless Steels, and Non-Ferrous Metals” (26). The bush-off blast was performed using a lower air pressure and a softer abrasive medium in the blasting chamber. Garnet (36 mesh) abrasive was used as the sandblasting medium and the blasting nozzle was applied at an angle between 30 and 60 degrees with a pressure between 40 and 45 psi and a quarter inch nozzle. The brush-off blast is intended to roughen up the surface of the galvanized steel and not to fracture the surface or remove the galvanization.

All samples were brush-off blasted the morning of application of the tie-coat. Prior to application samples were sprayed with high pressure air to remove any dust and debris that collected on the samples during sand blasting. Additionally, samples were inspected and if needed cleaned per SSPC-1 to remove any visible contaminants. Samples also had the thickness of the galvanized coating recorded using an eddy current film gauge. Figure 40 shows the comparison of a sample before and after brush-off blasting. In this figure the picture on the right has been brush-off blasted to a have a matte surface appearance.

Figure 40: Galvanized Brush-Off Blasting.

The surface profile of the galvanized samples was measured similar to the method for the non-galvanized samples. The only difference is that only Testex Coarse tape was used for these surface profile measurements. For surface profiled between 0.8 and 1.5 mils only Testex Coarse tape is used per Testex instructions. After brush off blasting every fifth panel had its surface profile measure. Table 12 has the measured surface profile for each panel measure. The average surface profile of the brush-off blasting on the galvanized samples was 1.2mils.

Table 13: Galvanized Surface Profiles

Profile Reading	Coarse Profile (mils)
1	1.2
2	1.2
3	1.2
4	1.2
5	1.3
6	1.0
7	1.1
8	1.0
9	1.2
10	1.1
Average	1.2

4.5 Application

The selected coating systems for this study were applied to steel and galvanized sample plates by two methods. All liquid coated test samples were prepared by the research staff who applied the coating materials to the surfaced-prepared test plates using a conventional spray equipment. For the powder coated test samples, all required galvanized test plates were prepared and transported by the research staff to a professional powder coating shop where they were powder coated as recommended by the manufacturer of the selected materials.

4.5.1 Liquid Coating Systems

The initial coat for each coating system in this study was applied to test plates within a few hours after the plates were solvent cleaned and sandblasted by the required surface preparation procedures explained in this report. All coating layers, except for PPG 2-coat system, were applied in a painting booth at Steel Wind Industries in Oak Creek, Wisconsin, see Figure 41. The PPG 2-coat system was a late addition to the test program and it was applied at a painting booth at University of Wisconsin Milwaukee's USR Building as shown in Figure 42.

Samples were allowed to dry for a minimum of 24 hours between applications of additional coating layers.

Figure 41: Steel Wind Painting Booth

Figure 42: UWM Painting Booth

All liquid coating systems were applied to test plates on wooden racks using a conventional spray-gun and a pressure pot. A Binks model 2100 conventional spray-gun with 66SD air nozzle, a 565 fluid needle, and 66SS fluid needle was used for spray coating application, see Figure 43. In addition, an air pressure regulator was attached to the spray gun for air pressure adjustments. The pressure pot was a two quart Binks model 80 with a fluid regulator.

Figure 43: Conventional Spray Gun and Pressure Pot

All test plates were sprayed using vertical paths in the top to bottom direction. The width of the spray allowed the entire panel to be completely covered with a single spray pass. To estimate the final dry film thickness for a layer of coating, a wet film gauge (tooth gage) was used as shown in Figure 44. To determine the needed wet film thickness for a desired dry film

thickness, the DFT is divided by the percentage of solids in a particular coating material. During the coating applications, coating materials were sprayed on test samples on experimental basis to determine the number of required passes to achieve the desired wet film thickness.

Figure 44: Wet Film Gauge

4.5.1.1 Conventional Liquid Coating Systems

Conventional liquid coating systems in this study were 2- or 3-coat coating systems that were applied to non-galvanized steel plates. All coatings were mixed per manufacturers' recommendations using a pneumatic mixer shown in Figure 45. If allowed and needed, coatings were thinned per manufacturers' recommendations and with the manufacturers-recommended thinners.

All conventional liquid coating systems had organic zinc primers as their first coat. These primers consisted of a three-component organic zinc coating. After mixing and prior to application of the zinc coatings, the zinc primers were passed through a #50 mesh sieve to remove any large zinc particles as shown in Figure 46.

Figure 45: Pneumatic Mixer

Figure 46: Zinc Coating Passing Through #50 Mesh Sieve

Samples were given a minimum of 24 hours to cure prior to application of successive coatings. Samples were also sprayed with compressed air to remove any dust or debris that may have collected on the samples before spraying additionally coatings. Figure 47 shows the application of a top-coat in a 3-coat coating system.

Figure 47: Application of Top-Coat

Prior to applying any subsequent coating layer on the test samples, the dry film thickness (DFT) was taken and recorded. A minimum of six DFT readings were taken for the 3 in. x 6 in. and 4 in. x 6 in. panels. For each test panel, three readings were taken both on the top and bottom portions of the exposure window. For the 2 in. x 2 in. samples a minimum of three DFT readings were taken in the central area of each sample. The final DFT was taken for all samples after the application and curing of the top-coat. Appendix B includes a list of all DFTs for the test panels tested in this study.

4.5.1.2 Duplex Liquid Coating Systems

All duplex coating systems in this study consisted of a tie-coat and a top-coat installed on a brush-off blasted galvanized steel test panels. Tie-coats were allowed to dry for a minimum of 24 hour before the application of the top-coat. Prior to application of the top-coat, samples were cleaned with compressed air to remove any dust or debris. Both the tie-coats and the top-

coats consisted of one- and two-component coatings. All coatings were mixed and thinned according to the manufacturers' recommendations.

The initial thickness of the galvanizing layer was measured for all samples prior to application of tie-coat. DFT values for all samples was obtained both after application of the tie-coat and after application of the top-coat. Appendix B includes a list of the galvanization thickness, tie-coat thickness, and top-coat thickness for all duplex liquid coating systems used in this study.

4.5.2 Duplex Powder Coating Systems

For the power coating systems in this study each tie-coat was applied on galvanized steel at a Sherwin Williams powder coating facility in Milwaukee, WI. Then, the samples were transported to Amour Coatings in Germantown, WI where they received appropriate top-coats. Before and after application of top-coats, DFT was measured by the research staff for all samples.

4.5.2.1 Initial Powder Coating

Samples were initially powder coated by professional staff at Armour Coating but they showed severe out-gassing craters. The out-gassing craters were attributed to the reaction of the tie-coat with the galvanized steel surfaces. An anti out-gassing agent was mixed into the powder before application to minimize the effects of out-gassing craters on the samples. After several trials using different percentages of the anti out-gassing agent, the out-gassing craters were minimized by approximately (80%) but were not totally eliminated on all samples.

The final powered coating was obtained with materials that consisted of a 2% mixture of anti out-gassing agent mixed into the tie- and top-coats prior to application. Figure 48 shows the reduction in the out-gassing craters (panel on the right) after the addition of the anti out-gassing

agent. The anti out-gassing agent is a waxing agent that is expected to minimize the effects of out-gassing craters in the samples.

Figure 48: Initial (left) and Final (Right) Out-gassing Craters

4.5.2.2 Final Powder Coating

The initial surface preparation of the galvanized samples was conducted by the research staff a few hours before application of the tie-coat. The samples were solvent cleaned, brush-off blasted, and cleaned with compressed air by the research staff and then transported to the Sherwin Williams powder coating facility. A 2% mixture of an anti out-gassing agent was mixed into the tie-coat and it was applied to all panels after prebaking the panels at 400°F for 10 minutes. The samples were then placed back into the oven and kept at 400°F for 15 minutes.

After application of the tie-coat, the samples were taken to Armour Coatings where the top-coat was applied. A 2% mixture of the anti out-gassing agent was also mixed into the top-

coat before application. The samples had the top-coat applied and then they were baked in the oven at 400 °F for 15 minutes.

5.0 Results and Discussion

5.1 Introduction

Performance of all coating systems selected for this study was evaluated based on the analysis of the results from the conducted investigation. Various evaluation parameters were considered in the study to determine rankings of the selected coating systems. Recommendations on selection and application of coating systems for bridge railings were made to WisDOT and suggested language was provided for relevant WisDOT Standard Specification and Special Provisions.

5.2 Accelerated Weathering Results

5.2.1 Freeze/UV/Prohesion Testing

Results from exposure of all coating systems in the study to cyclic freeze/UV/Prohesion testing were obtained and evaluated to assess coating performance for both aesthetic and protection against corrosion. The analysis of the results was made by considering the following influencing parameters:

5.2.1.1 Color Retention

For aesthetic purposes, color retention properties of a coating system is one of the most important factors to consider. After completion of each cycle of accelerated weathering test, all coating samples in the study were monitored for changes in color by measuring and recording the L, a, b color indexing values under the CIELAB model. The root mean square, ΔE, of the measured L, a, b values were calculated each time based on the initial values of L, a, b taken initially on the control samples. The calculated ΔE values were evaluated to determine any changes in color for the coating systems of this study for the duration of the test. It must be noted that by considering only the ΔE values, one can only draw a conclusion on changes in the color but not the direction of the change, i.e., lightness or changes in color range between black

and white, changes in color range between green and red, or changes in color range between blue and yellow. In order to have a better insight regarding these more specific changes in color, values of ΔL, Δa, and Δb were also calculated by considering the L, a, b values from both the initial measurements on the control samples and those measured after each test cycle. In addition, since the exposure window for each sample in the UV chamber was smaller than its full size, visual comparisons could be made at the end of each test cycle for changes in color due to only the UV exposure effect. Table 13 and Figure 49 show the final ΔE, ΔL, Δa, and Δb values at the completion of the accelerated weathering test for each coating system that were included in this study. Figure 50 shows the ΔE values for all of the coating systems as calculated after completion of each test cycle throughout the complete accelerated weathering test. A complete list of color retention values for each cycle is included in Appendix B of this report.

Table 14: Final ΔE and ΔL, Δa, Δb Values

Coating System	ΔE	ΔL	Δa	Δb
CB-2	1.29	1.18	0.07	-0.53
PPG-2	8.24	8.03	-0.21	-1.85
CB-D	1.37	1.35	0.08	-0.25
SW-D	0.51	0.22	0.15	-0.41
WA-D	0.95	-0.78	0.11	-0.52
CB-3P	1.46	1.41	0.11	-0.37
SW-3P	0.71	0.49	0.14	-0.48
PPG-3P	2.72	2.64	-0.02	-0.69
CB-3F	0.41	0.32	0.25	-0.03
SW-3F	0.81	0.69	0.15	-0.38
SW-05PD	0.28	-0.25	0.13	-0.04
SW-04PD	5.08	4.78	-0.31	-1.70

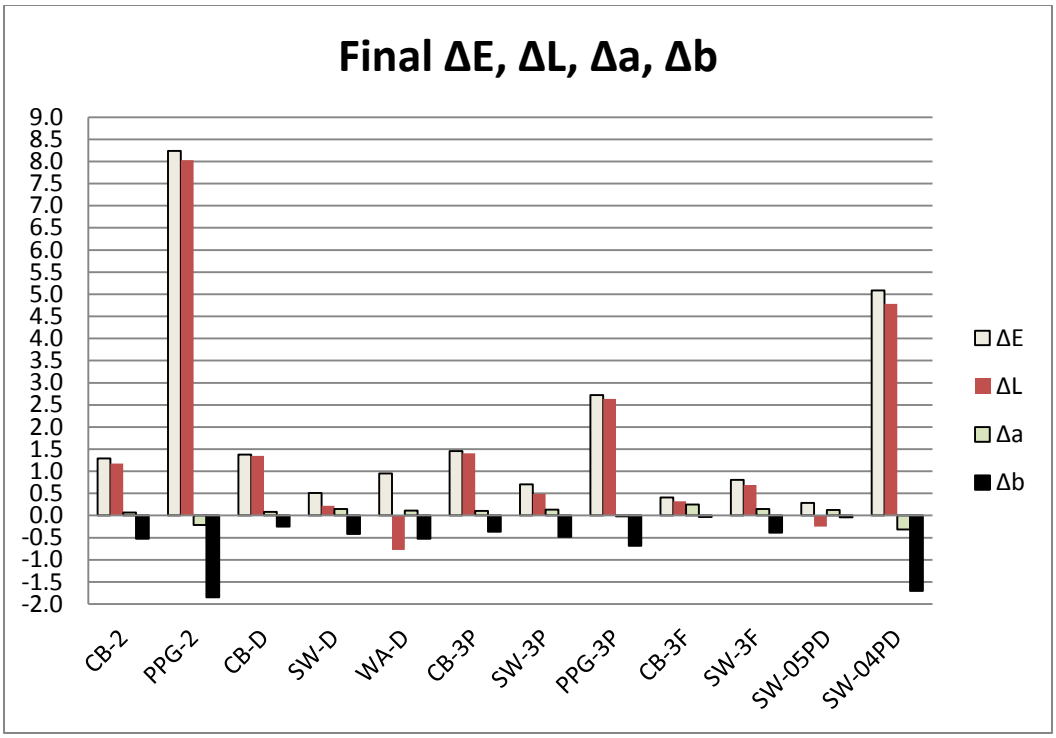


Figure 49: Final ΔE and Final ΔL, Δa, Δb

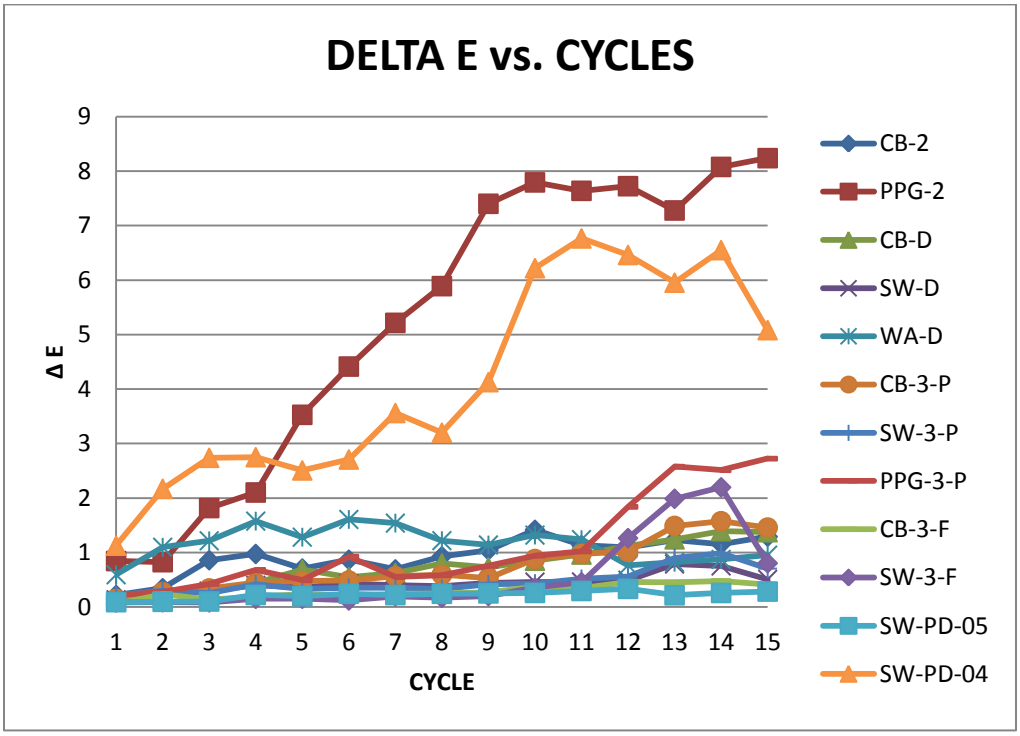


Figure 50: ΔE per Cycle

Since all of the coated samples used in the weathering test had a black color top-coat, the significance of the measured changes in the L values is more apparent as they define changes in lightness or changes in color range between black and white. It is apparent from an evaluation of the results shown in Table 13, and Figures 49 and 50, that coating systems with highest values of ΔE also exhibited high values of ΔL. Changes in the values of L, or ΔL, at each cycle throughout the accelerated weathering test were measured and recorded as shown in Figure 51.

Coating systems PPG-2 and SW-04PD exhibited the highest ΔE values as well as high values of ΔL. Two coatings systems WA-D and SW-05PD exhibited negative small ΔL values which indicated that the initial color became somewhat darker on the color indexing scale. However, an examination of photographs taken for control samples coated with WA-D coating system and of those taken after completion of a selected number of test cycles reveals that the color actually became lighter, see Figure 63. This is believed to be due to the change or reduction in the gloss of the coating system which caused the color to appear lighter. In contrast, the appearance of a dark color in coating system SW-05PD after the completion of the weathering test confirms the above conclusion. The confirmation is due to the small level of loss of gloss as shown by the measured and recorded values for this coating system.

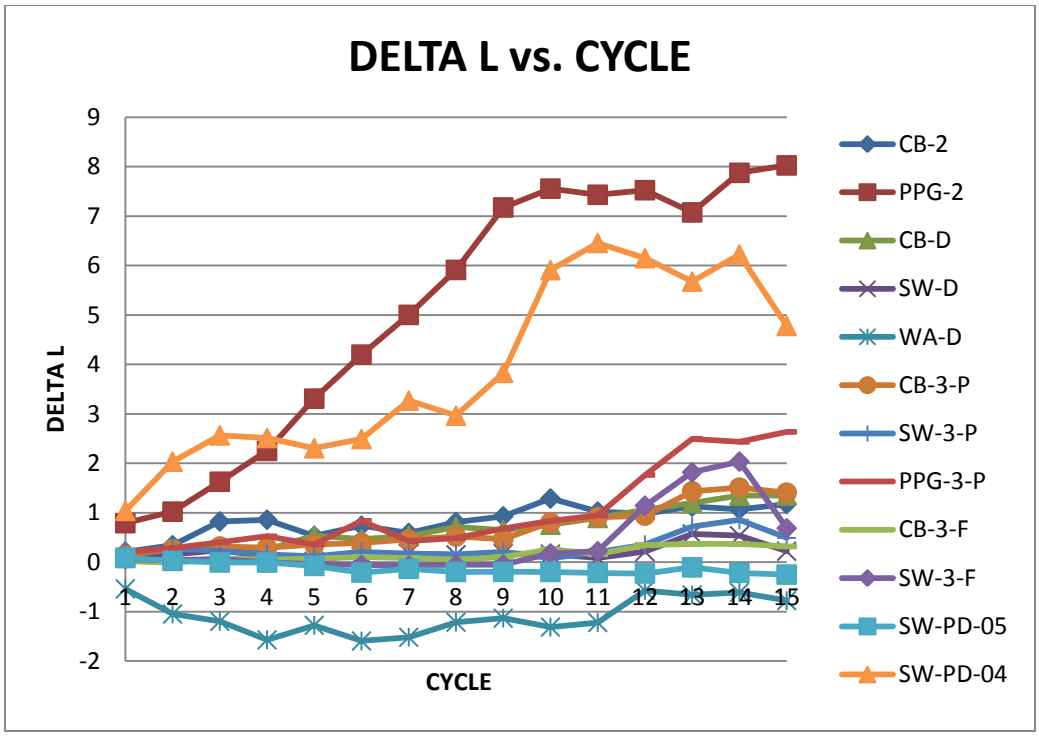


Figure 51: ΔL per Cycle

For samples coated with a black color, the color change may be represented by the values of absolute ΔL which corresponds well with the overall change in color as measured by ΔE. Figures 52 and 53 show relations between ΔE and absolute ΔL and between ΔE and ΔL, respectively, based on performing a linear regression analysis. Figure 54 shows side-by-side values of ΔE and absolute values of ΔL for all coating systems included in this study.

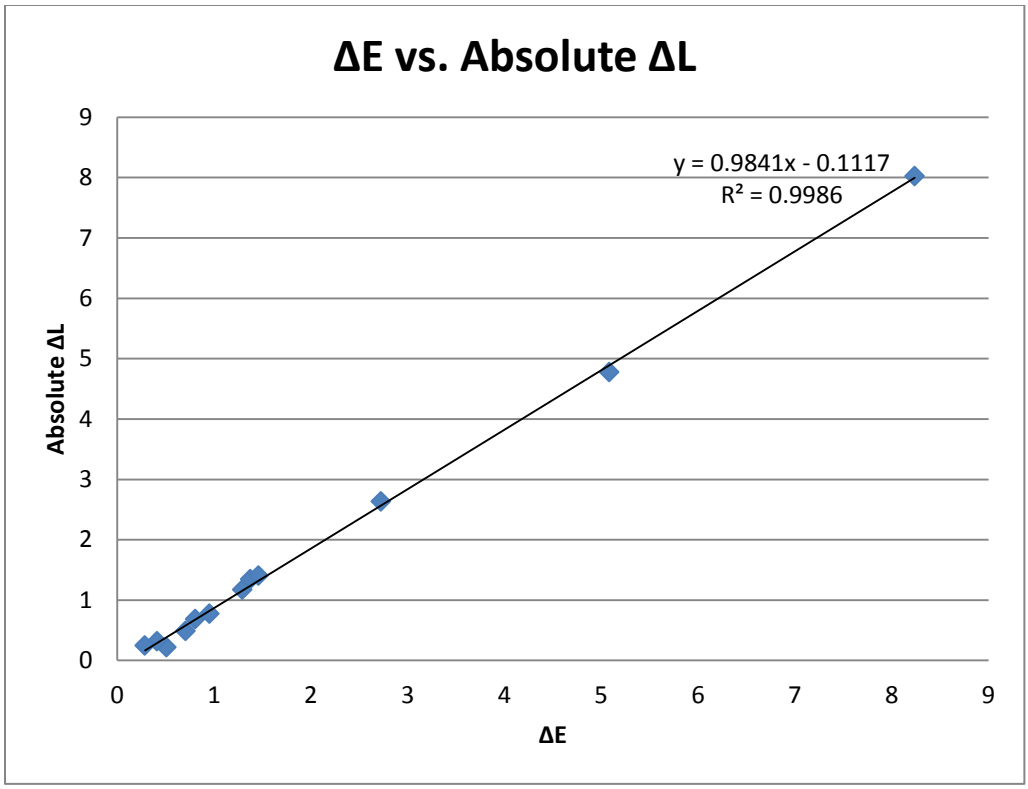


Figure 52: Linear Regression: ΔE vs. Absolute ΔL

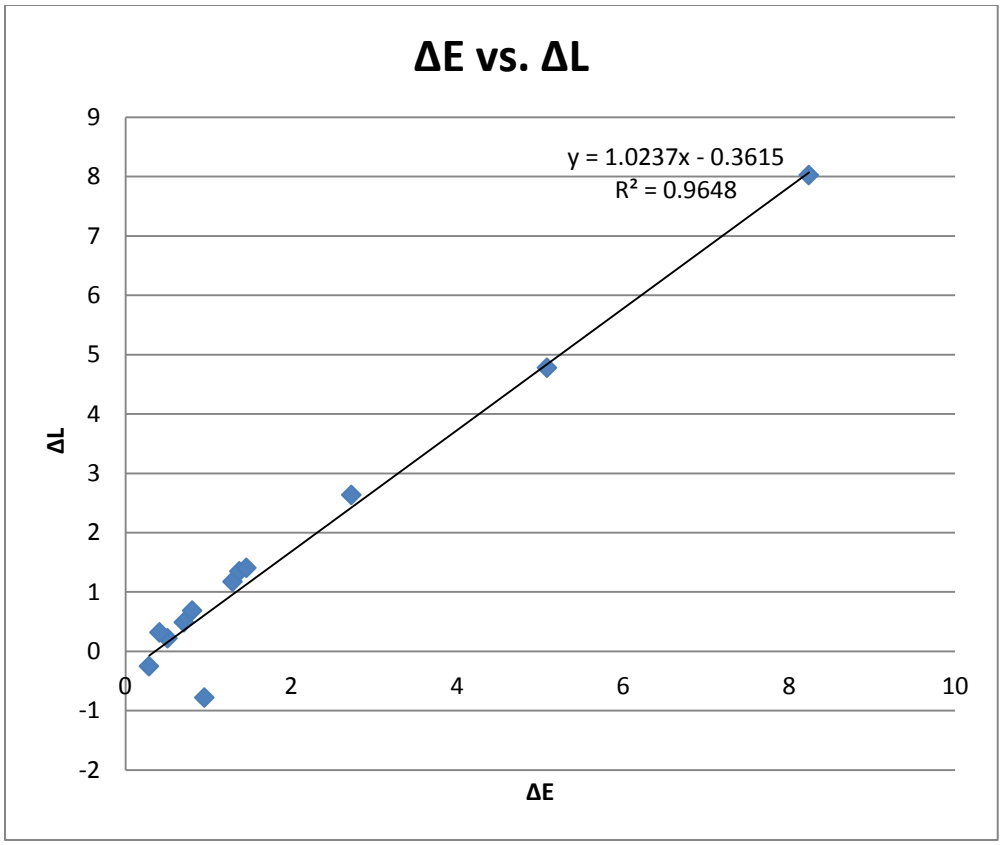


Figure 53: Linear Regression: ΔE vs. ΔL

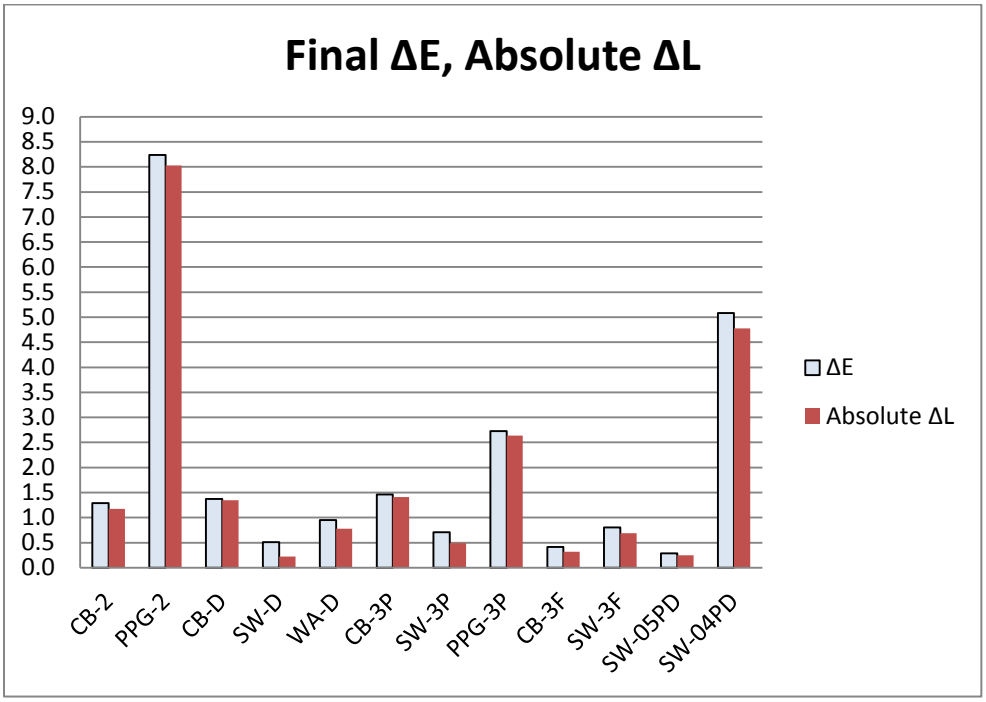


Figure 54: Final ΔE and Absolute ΔL

One of the two 2-coat systems, coating system PPG-2, exhibited a significantly high value of ΔE (ΔL = 8.03) after the completion of the weathering test. Both coating systems contained zinc-rich primers with polysiloxane top-coats. A visual examination of the surfaces of the coated samples for the PPG-2 coating system confirmed that a reduction of darkness in the color occurred with exposures to the cycles of weathering test during this study. Figure 55 shows photographs taken from the control sample prior to the weathering test and those taken of the sample after cycle 5, cycle 10, and cycle 15 of the test, respectively. A significant change in color is observed throughout these test cycles. Figure 56 shows the change in color for coating system CB-2. Color fading in this coating system is not as prominent as coating system PPG-2. The results from this study are similar to those from other studies that have shown that some 2-coat systems have performed well and similar to polyurethane coatings while others have had poor results.

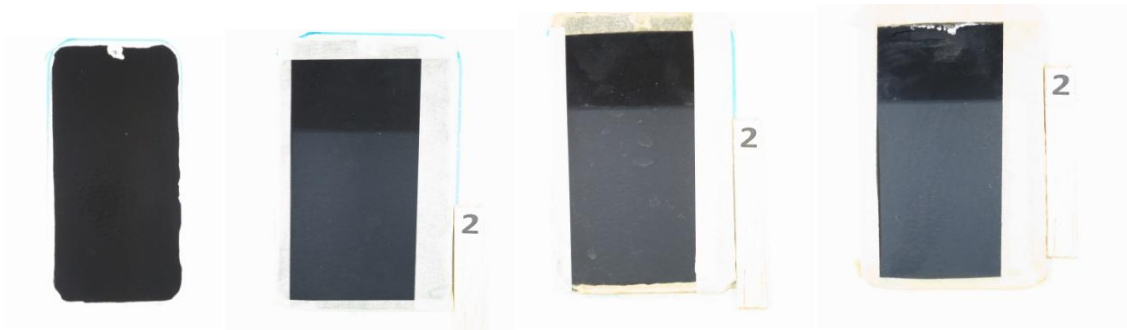


Figure 55: PPG-2 Initial, Cycle 5, Cycle 10, Cycle 15

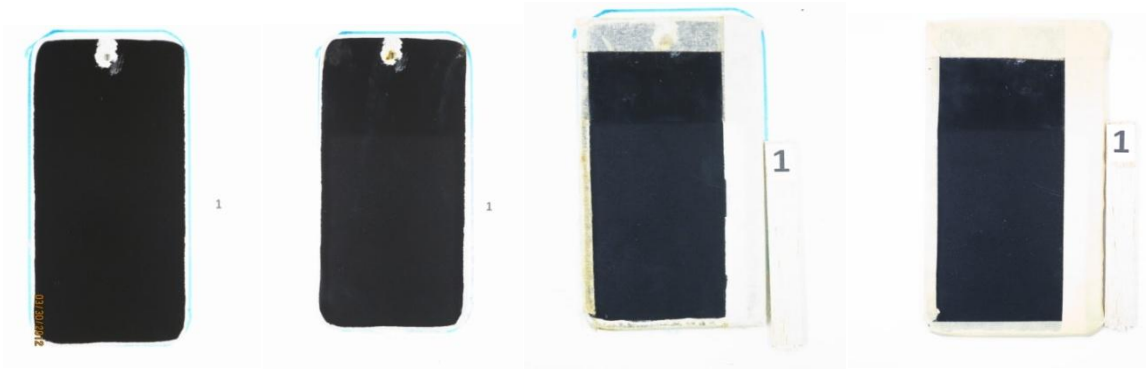


Figure 56: CB-2 Initial, Cycle 5, Cycle 10, Cycle 15

Of the 12 coating systems tested in this study, 6 systems had urethane/polyurethane top-coats. Some of the coating systems, including duplex systems, had the same top-coat. For example, coating systems CB-D and coating system CB-3P had the same top-coat (Carbothane 133LH). Also, coating systems SW-D and SW-3P had the same top-coat (Acrolon 218 HS). Accordingly, the performance of these coating systems were generally the same when color fading is considered. Figure 57 shows the final ΔE values for the coating systems with the same top-coat and Figure 58 shows the ΔE values for each cycle for the same coating systems. As shown in these figures, the ΔE values for these coating systems follow similar trends throughout the cycles as well as when the final ΔE values are considered.

The other two urethane/polyurethane coatings included in this study were WA-D and PPG-3P. Figures 63 and 64 show photographs taken for the control samples and for the same samples after exposure to different cycles of the weathering test. Coating system WA-D had a moderate level of color fading and the PPG-2 system showed a slightly higher change in color when compared to the other polysiloxane coating systems. As shown in Figure 57, the PPG-3P coating system exhibited the greatest color change (ΔE) and coating system SW-D experienced the least color change (ΔE).

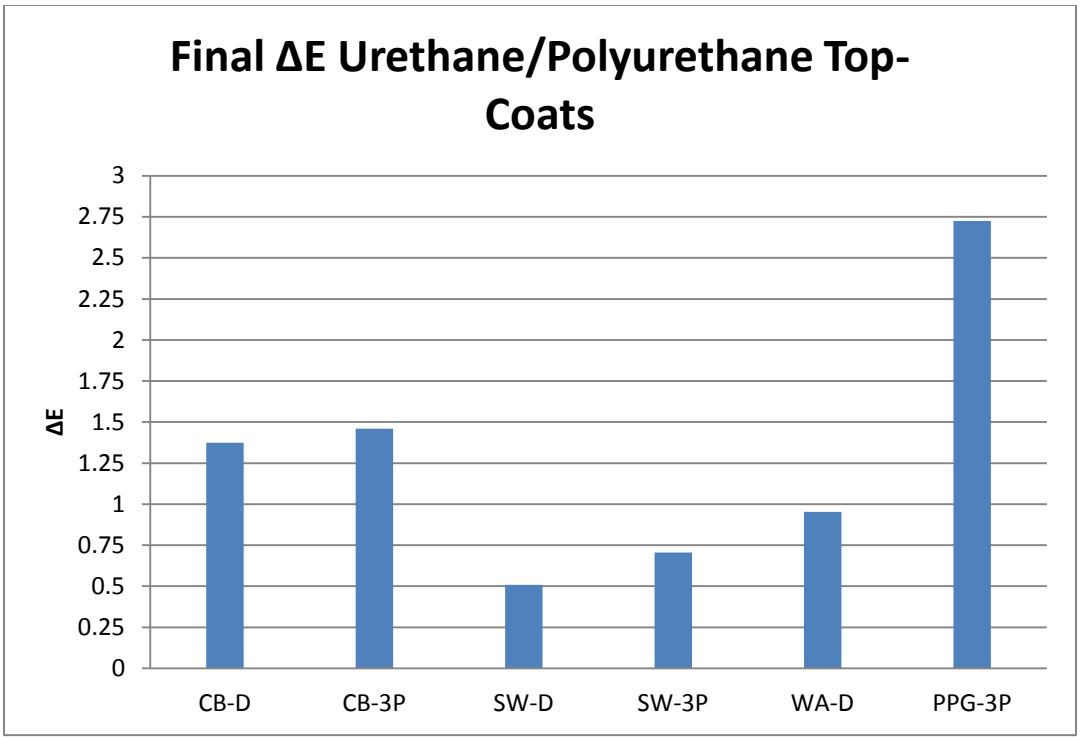


Figure 57: Final ΔE for Urethane/Polyurethane Coatings (CB-D, CB-3P, SW-D, SW-3P, WA-D, PPG-3P)

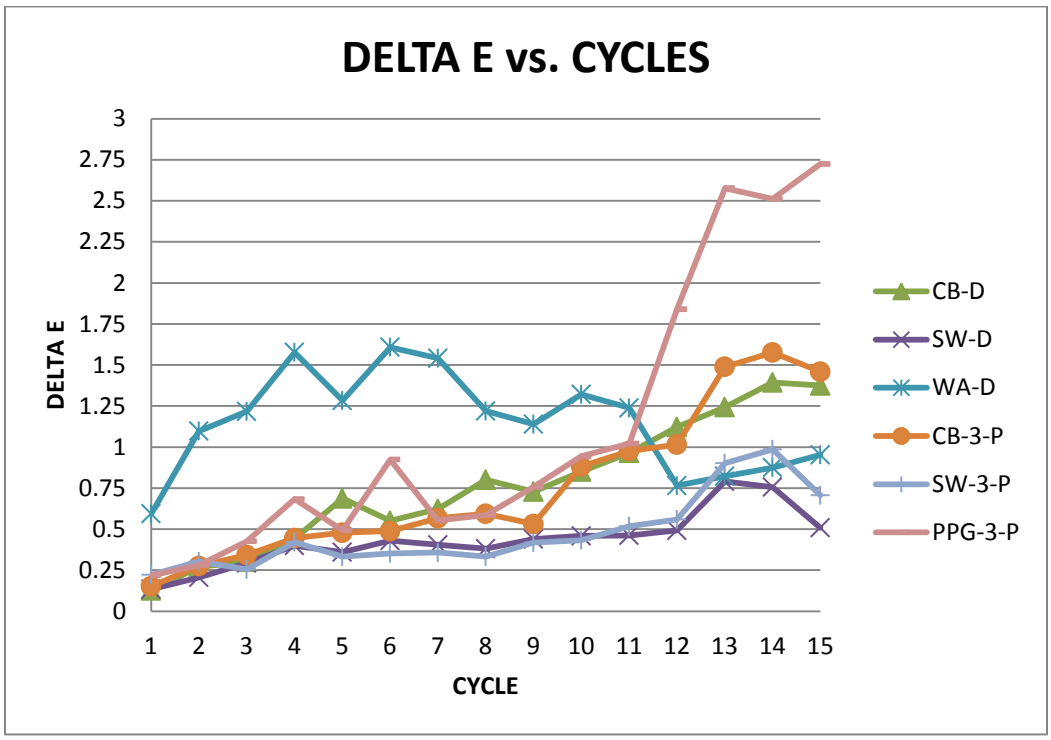


Figure 58: Cycles vs. ΔE for Urethane/Polyurethane Coatings (CB-D, CB-3P, SW-D, SW-3P, WA-D, PPG-3P)

Figure 59: CB-D Initial, Cycle 5, Cycle 10, Cycle 15

Figure 60: CB-3P Initial, Cycle 5, Cycle 10, Cycle 15

Figure 61: SW-D Initial, Cycle 5, Cycle 10, Cycle 15

Figure 62: SW-3P Initial, Cycle 5, Cycle 10, Cycle 15

Figure 63: WA-D Initial, Cycle 5, Cycle 10, Cycle 15

Figure 64: PPG-3P Initial, Cycle 5, Cycle 10, Cycle 15

There were three different fluoropolymer coating systems that were included in this study. Among these, two were 3-coat zinc systems (SW-3F and CB-3F), and one was a duplex powder coated system (SW-05PD). Coating systems SW-05PD and CB-3F resulted in the lowest

final ΔE values among all the coating systems in the study. Figure 68 shows the ΔE values for the fluoropolymer coating systems throughout the test cycles. Figures 65, 66, and 67 show photographs of the control samples as well as those for the same samples after exposure to Cycle 5, Cycle 10, and Cycle 15 of the weathering test for coatings systems SW-3F, CB-3F, and SW-05PD, respectively. As shown in these figures, coating systems SW-05PD and CB-3F have practically undistinguishable color changes. Fluoropolymer coating systems exhibited the lowest overall color changes in this study due to their strong physical properties and exceptional resistance to color fading.

SW-3F had similar ΔE values as the other two fluoropolymer coatings until it began to have white spots appearing at cycle 9. These white spots varied each cycle until completion of the test. Since these white spots varied in location, the ΔE values also varied depending on the location and frequency of the white spots. At completion of the accelerated weathering testing, the samples were cleaned with the goal of removing these spots from the surface. A variety of different methods were used that included: cleaning with deionized water, vinegar, mineral spirits, and acetone. Water, vinegar, and mineral spirits did not have any effect on removing these spots. Acetone was effective in removing the spots, but it resulted in a slightly dull surface appearance for the coating. The spots appeared to be only on the surface and not within the thickness of the entire top-coat.

Performance of fluoropolymer coating systems with respect to color fading was only slightly better than that for the polyurethane systems that were included in this study. When comparing coating system CB-3F and SW-D, the difference in the measured value of the ΔE was equal to 0.1 indicating practically the same as well as very small level of color fading. Although the difference in the calculated ΔE values was not large, a distinct difference in color fading performance was observed for the two coating systems. An examination of Figure 66 shows a

very small level of color change for the fluoropolymer coating system while a more prominent color change can be seen for the SW-D system, see Figure 61. The noticeable change in color for coating system SW-D is also due to the higher reduction in gloss when compared to the fluoropolymer coating system.

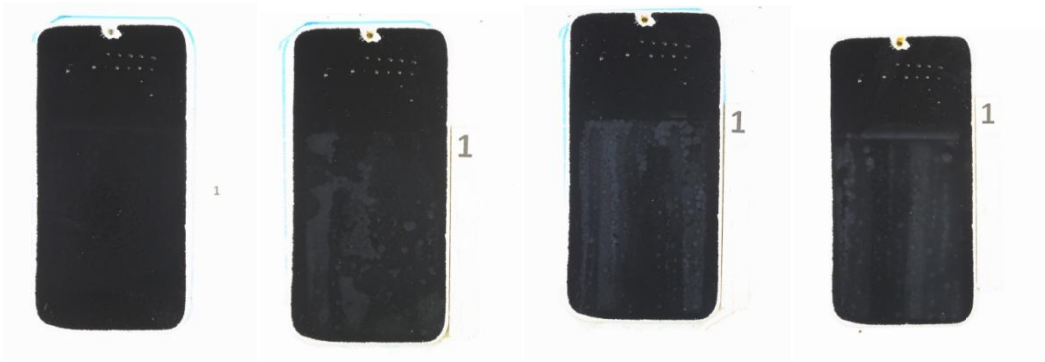


Figure 65: SW-3F Initial, Cycle 5, Cycle 10, Cycle 15

Figure 66: CB-3F Initial, Cycle 5, Cycle 10, Cycle 15

Figure 67: SW-05PD Initial, Cycle 5, Cycle 10, Cycle 15

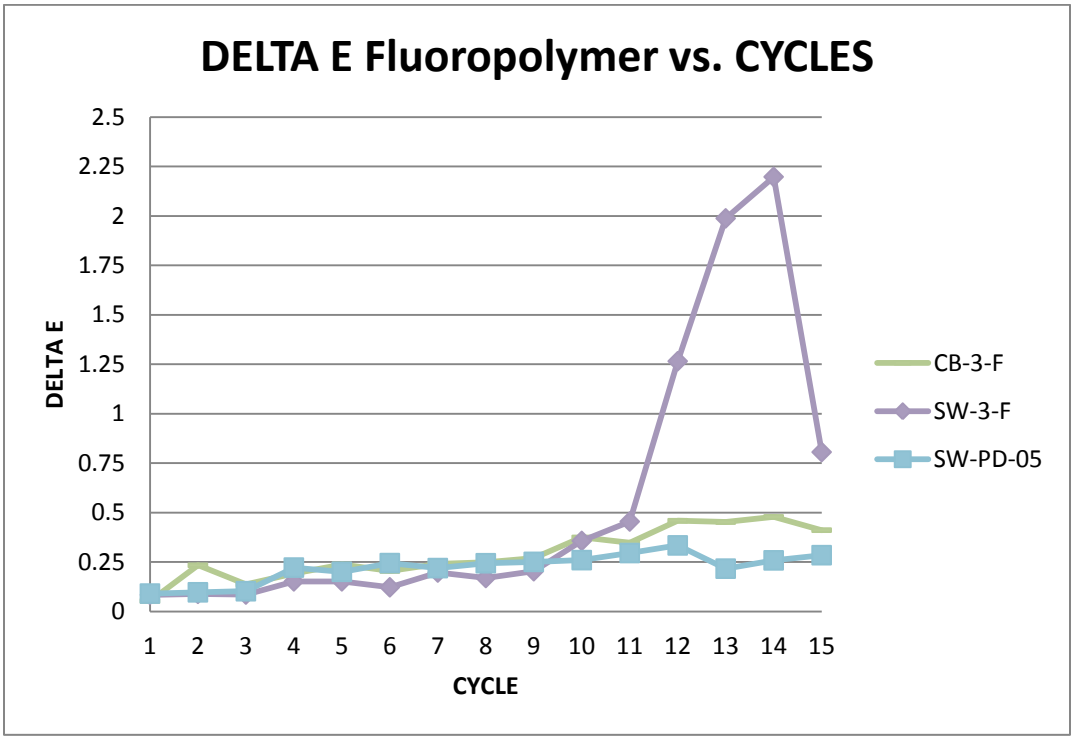


Figure 68: ΔE Fluoropolymer Coating Systems (SW-3F, CB-3F, SW-PD05)

The study also included powder coated duplex systems with a polyester top-coat (SW-04PD), see Figure 69. This coating system exhibited the second largest ΔE values when compared with all of the coating systems that were subjected to the accelerated weathering test. This coating system experienced a noticeable change in color even after the first cycle of weathering exposure. Polyester powder coat systems were marketed as mid-grade systems while the fluoropolymer was marketed as a producing top-grade powder coat systems.

Figure 69: SW-04PD Initial, Cycle 5, Cycle 10, Cycle 15

5.2.1.2 Gloss Retention

Although not as profound appearance as color retention, gloss retention is another factor affecting the overall aesthetics of coating systems. The coating aesthetic is adversely affected by loss of gloss on bridge railings particularly in areas that are subjected to more sunlight,

Each of the coating systems in the study had a specific level of gloss after the application and curing of the coating systems on galvanized and non-galvanized steel plates. The initial Gloss values, or angles, ranged from a low level of 25° to as high as 85° for all the control coating samples in the study. All measured gloss values for each accelerated weathering test cycle are shown in Figure 70 and a comparison between the initial and final gloss values is shown in Figure 71. Since the initial gloss values are different for the coating systems, the percent change in gloss values were used to evaluate the coating systems. Figure 72 shows the percent change in gloss values for each weathering test cycle and Figure 73 shows the final percent change in gloss values for all coating systems in the study. Since all gloss values decreased as the weathering test progressed, the percentage of change in gloss in Figures 72 and 73 is considered as the percentage of loss of gloss for the coating system. A complete list of gloss loss values for all coating systems is shown in Appendix B.

Among the coating systems included in this study, systems with fluoropolymer top-coat exhibited the lowest percentage of reduction in gloss with SW-05PD having the lowest gloss loss, followed by SW-3F and CB-3F. The next lowest loss of gloss was shown by polysiloxane 2-coat systems with coating system CB-2 having a 22% reduction in gloss and PPG-2 having a 32% gloss loss. Although coating system PPG-2 had the greatest change in color, it did not have a high percentage of reduction in gloss when compared with the other coating systems. Polysiloxane coatings are generally known to have superior weathering characteristics similar to or slightly better than polyurethanes which found to be in support of the experimental results of this study.

The urethane/polyurethane coating systems in the study showed a reduction in gloss ranging from 35% to 61% with the exception of coating system WA-D which showed a 95% reduction in gloss. Again, the coating system with the same top-coats (SW-D, SW-3P and CB-D, CB-3P) experienced similar gloss reduction. Finally, coating system SW-04PD with its polyester powder top-coat experienced a reduction in gloss of 45%. This reduction was similar to other polyurethane coatings with the exception of coating system WA-D.

Duplex powder coated systems, SW-04PD and SW-05PD, were the only two coating systems that exhibited higher gloss values only after the initial weathering cycles. For SW-04PD, the gloss increased after the first cycle and then progressively decreased in proceeding cycles. For SW-05PD, the increase in gloss occurred after the first weathering cycle with no changes until the completion of the study. While the increase in gloss was not significant, at most 5%, it is believed that it was due to the anti out-gassing (paraffin) agent that was added to the coating. The added paraffin appeared to have deposited a film on the surface of the samples and its effect was possibly diminished after1 to 3 cycles of weathering exposure. The initial samples were cleaned with a wet cloth prior to testing, but the film still remained on the samples.

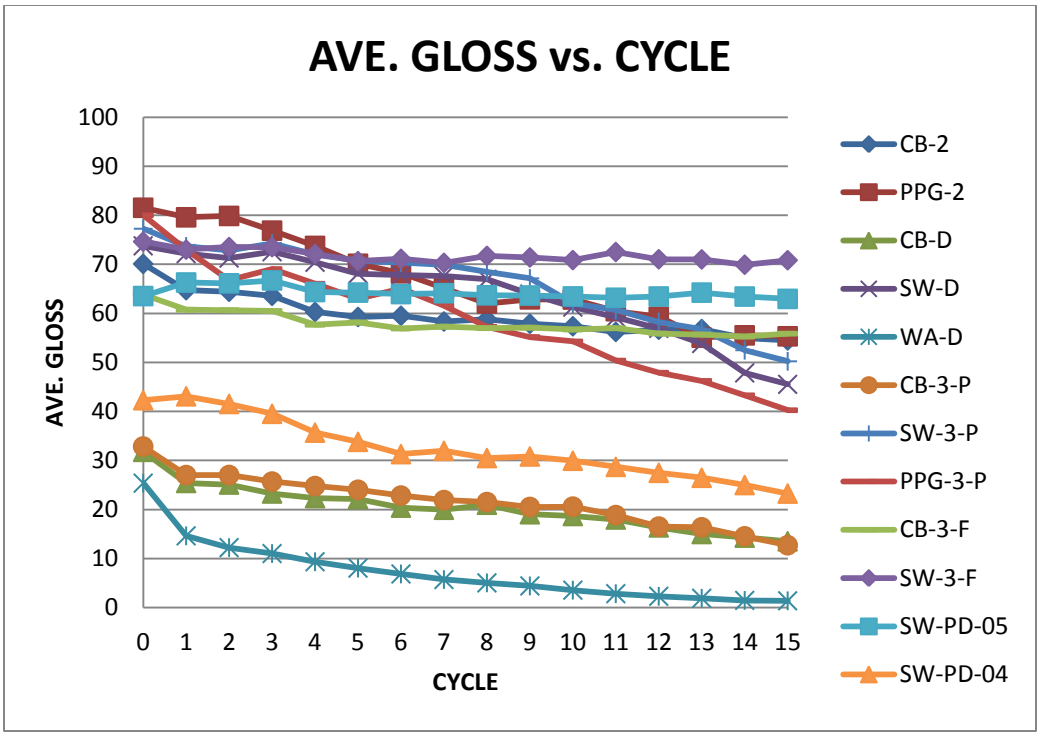


Figure 70: Gloss Values per Cycle

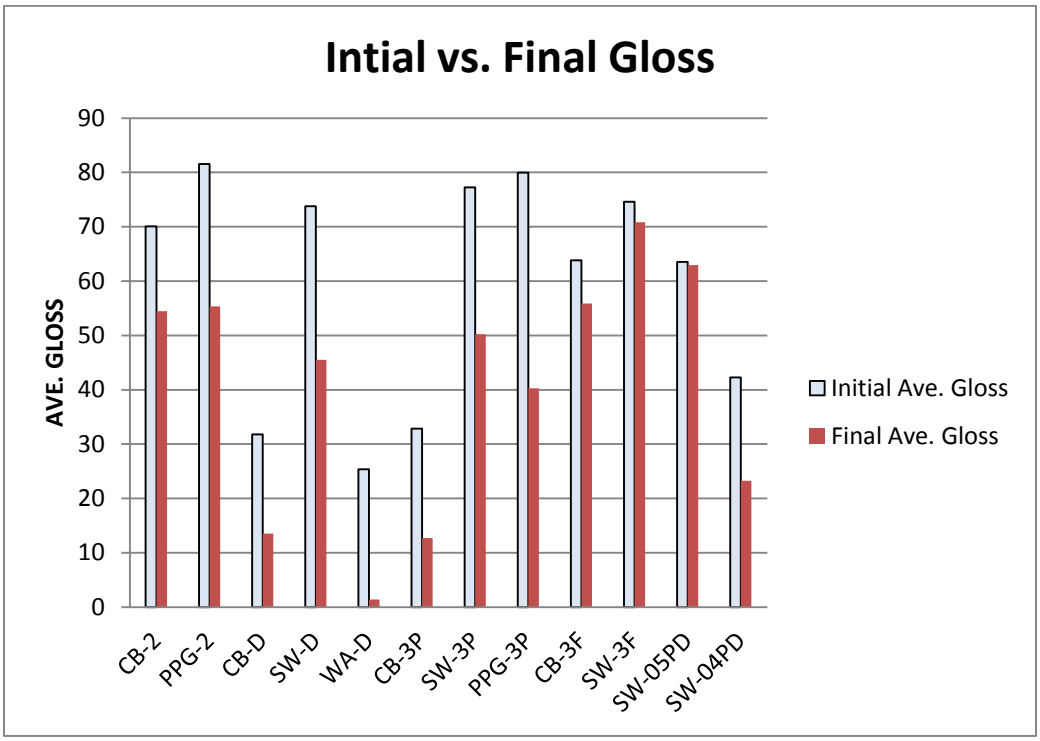


Figure 71: Initial and Final Gloss

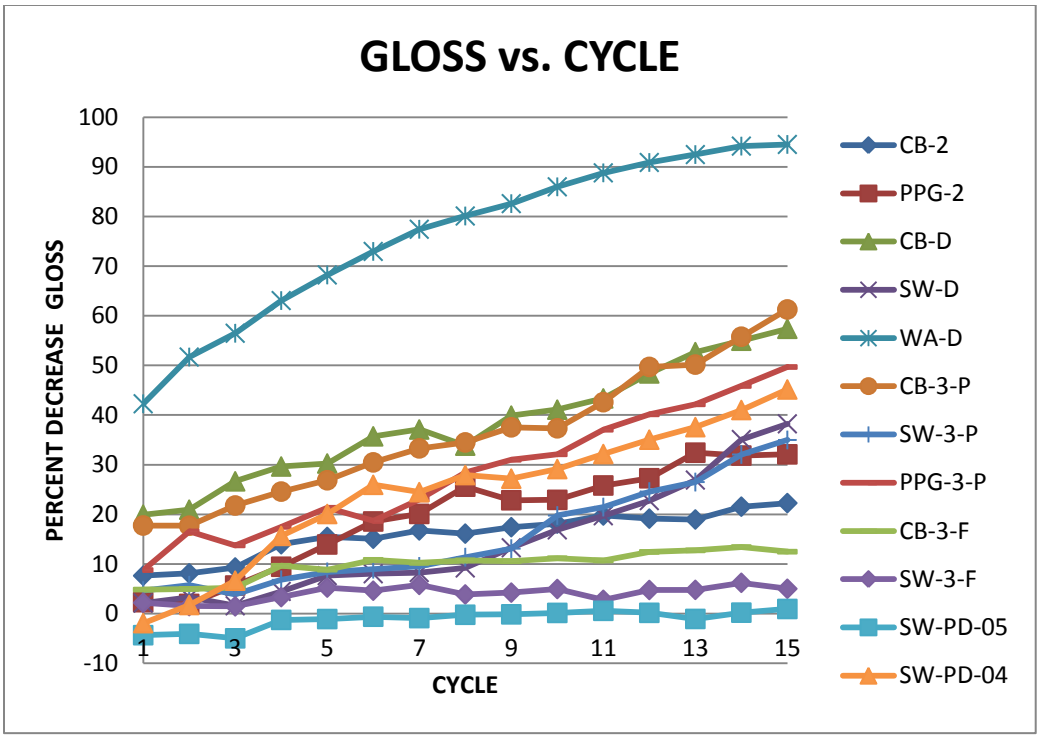


Figure 72: Percent Change in Gloss per Cycle

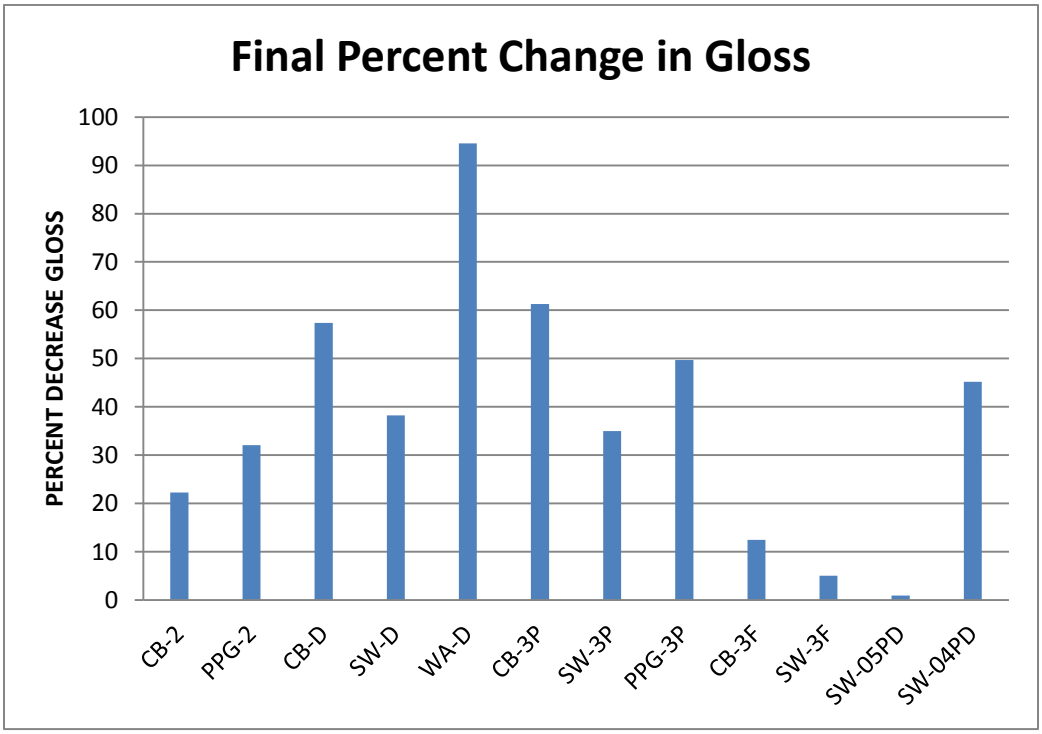


Figure 73: Final Percent Change in Gloss

5.2.1.3 Rust Creepage

Physical damage, such as scratches or dents, can have an important adverse effect on the performance of coating systems in terms of protection against corrosion. To evaluate the performance against such damage for coating systems used in this study, a series of rust creepage test was performed according to ASTM D7087-05a standard.

Two samples for each coating systems were scribed prior to testing and the rust creepage about the scribe was measured and evaluated at the completion of each accelerated weathering test cycle. The average rust creepage value of the two samples was used for analysis and evaluation. No coated sample showed evidence of rust creepage before the completion of the 7th cycle of the weathering test and some coated sample showed no evidence of rust creepage after the completion of the weathering test. Figure 74 shows the measured net mean creepage values for all of the coating systems that experienced rust creepage about the scribe. In addition, Table 14 and Figure 75 show the final measured values of net mean rust creepage for the affected samples. Figures 76 through 82 show photographs taken for the control samples and those from samples subjected to different test cycles for the coating systems that experienced rust creepage about the scribe. Figures 83 through 87 show photographs of the coating systems that did not exhibit any rust creepage about the scribe.

Of the five duplex systems, including liquid and powder coating systems, only one coating system (WA-D) experienced a mild level of rust creepage about the scribe. In coating system WA-D there was some rust creepage and undercutting of the coating. Coating system SW-3F was the only non-duplex coating system that did not experience rust creepage. There was some rusting in the scribe for this coating system, but there was no rust creepage of the coating system. Similarly, coating system SW-3P which had the same primer and mid-coat as SW-3F only experienced slight rust creepage. Coating systems CB-3F and CB-3P experienced

similar rust creepage values. Again, the better performance for the duplex systems was expected since the galvanization and epoxy mid-coats provided extra protection against corrosion.

Similar rust creepage results were obtained for both 2-coat system CB-2 and 3-coat systems CB-3F and CB-3P. These coating systems were made by the same manufacturer and had the same zinc-primer as their primer coat.

NEPCOAT recommends that acceptable rust creepage performance in coating systems should have their measured mean rust creepage values to be smaller than 0.16 in. (18). Accordingly, it is concluded that all coating systems in this study have had acceptable performance while some exhibited superior performance.

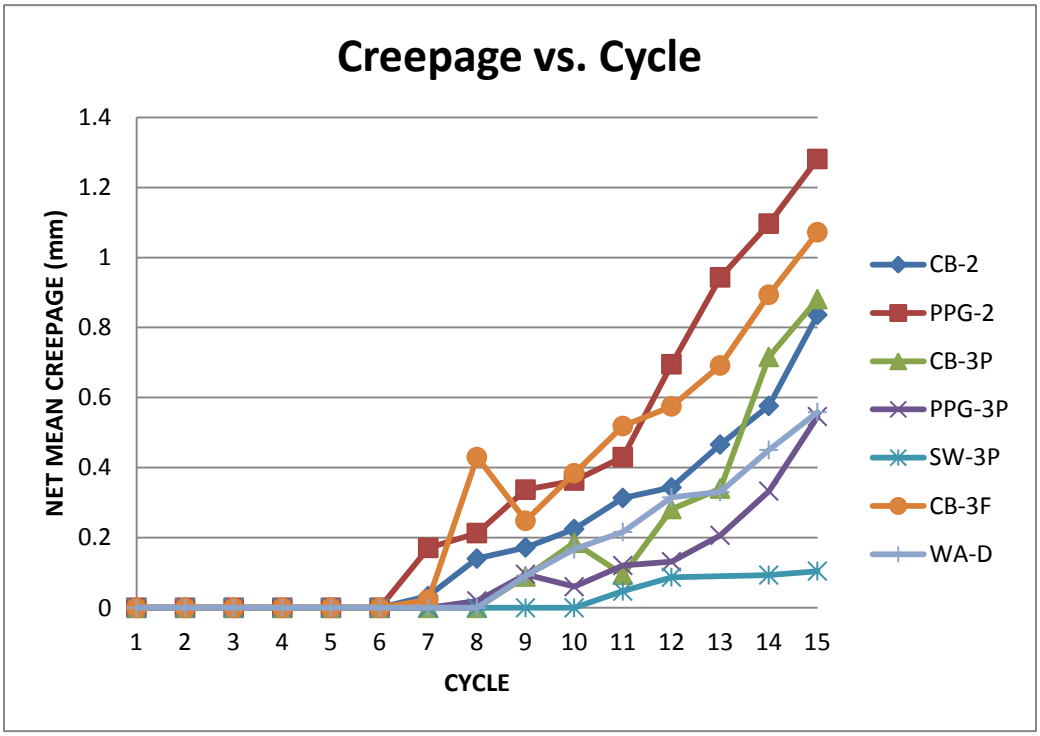


Figure 74: Net Mean Creepage per Cycle

Table 15: Final Net Mean Rust Creepage Values

Coating System	Net Mean Creepage (mm)
CB-2	0.886
PPG-2	1.231
CB-3P	0.931
PPG-3P	0.596
SW-3P	0.105
CB-3F	1.122
WA-D	0.608
CB-D	0
SW-D	0
SW-3F	0
SW-05PD	0
SW-04PD	0

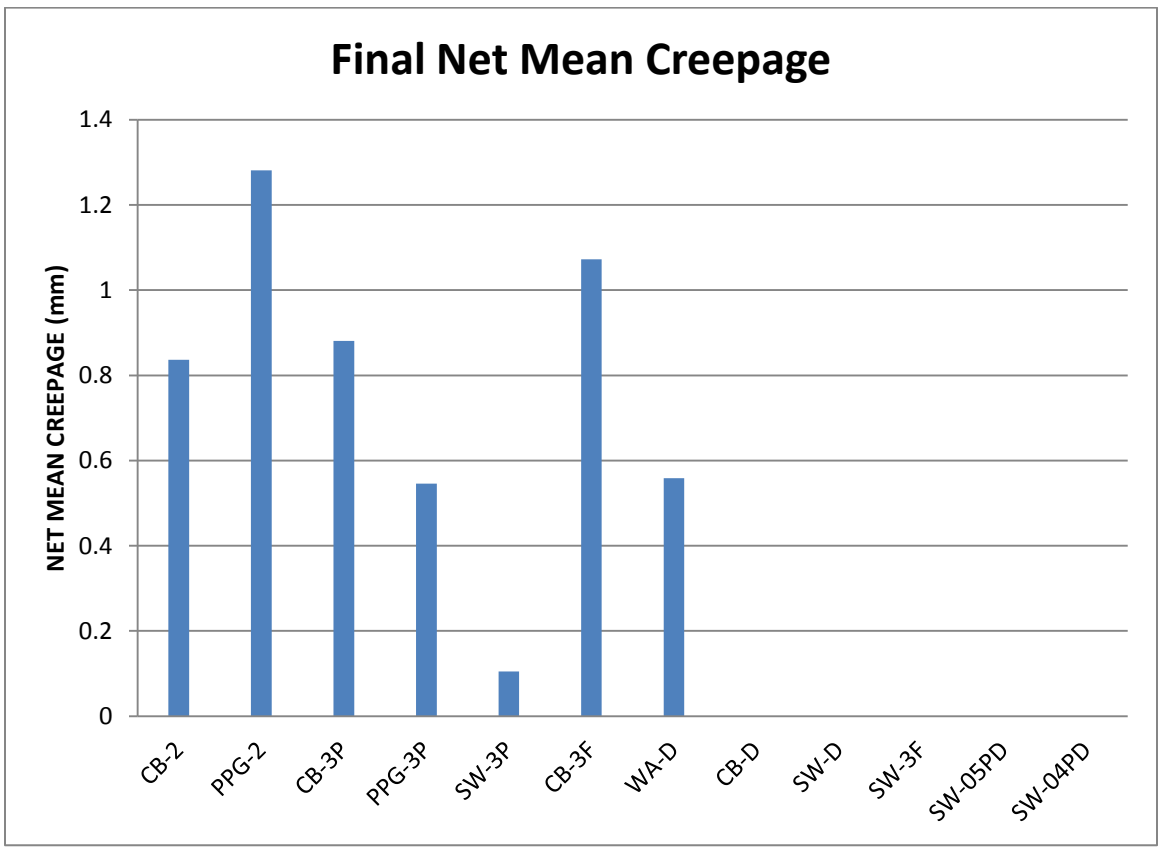


Figure 75: Final Net Mean Creepage

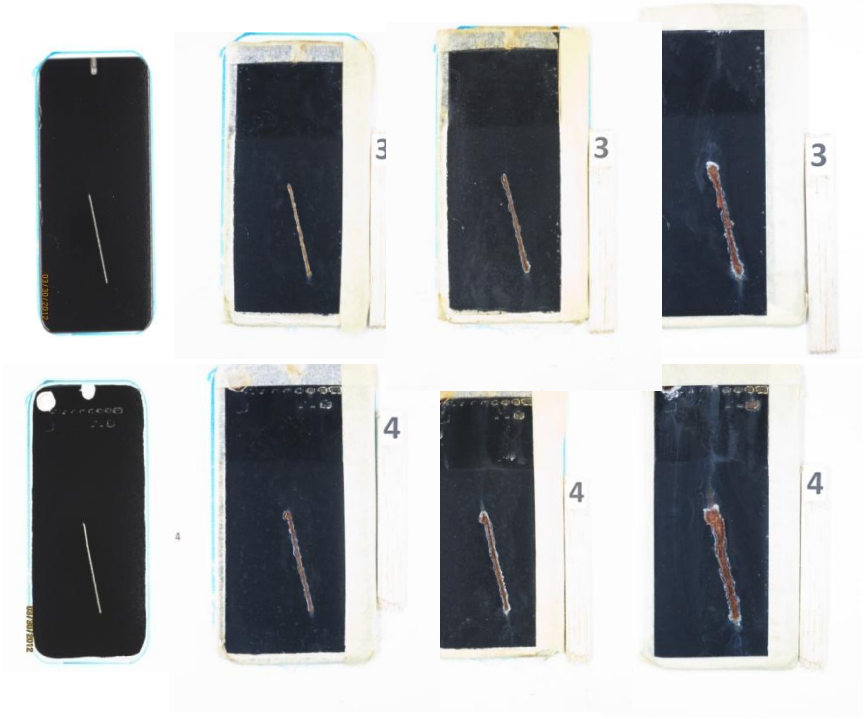


Figure 76: CB-2 Initial, Cycle 9, Cycle 12, Cycle 15

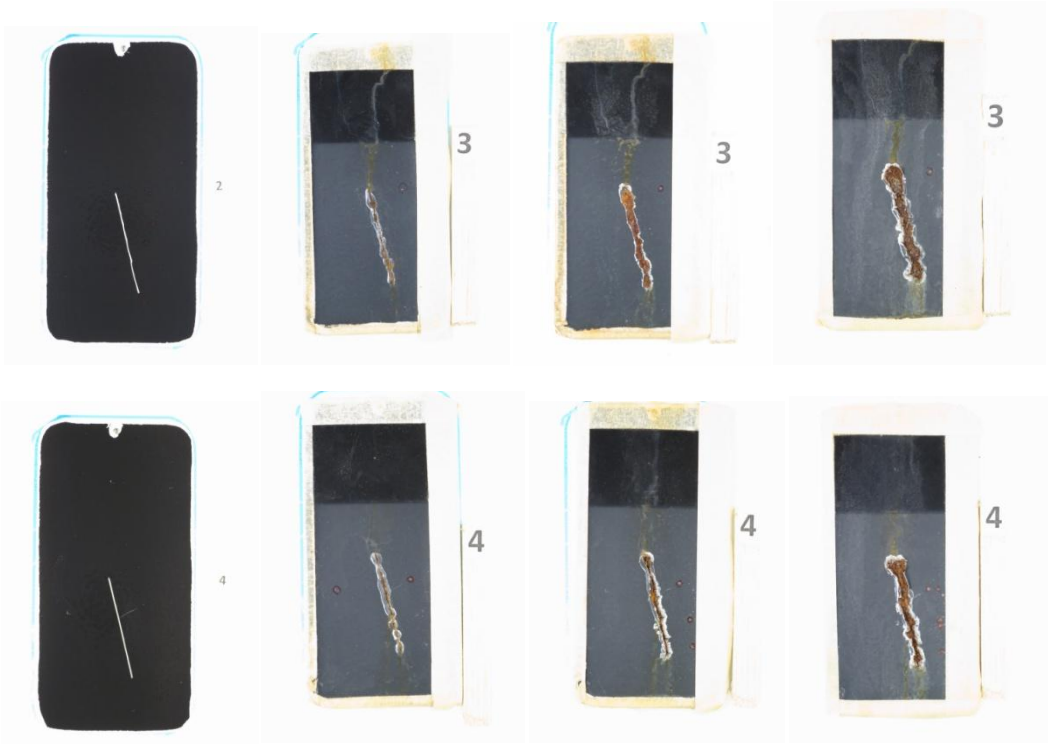


Figure 77: PPG-2 Initial, Cycle 9, Cycle 12, Cycle 15

Figure 78: CB-3P Initial, Cycle 9, Cycle 12, Cycle 15

Figure 79: PPG-3P Initial, Cycle 9, Cycle 12, Cycle 15

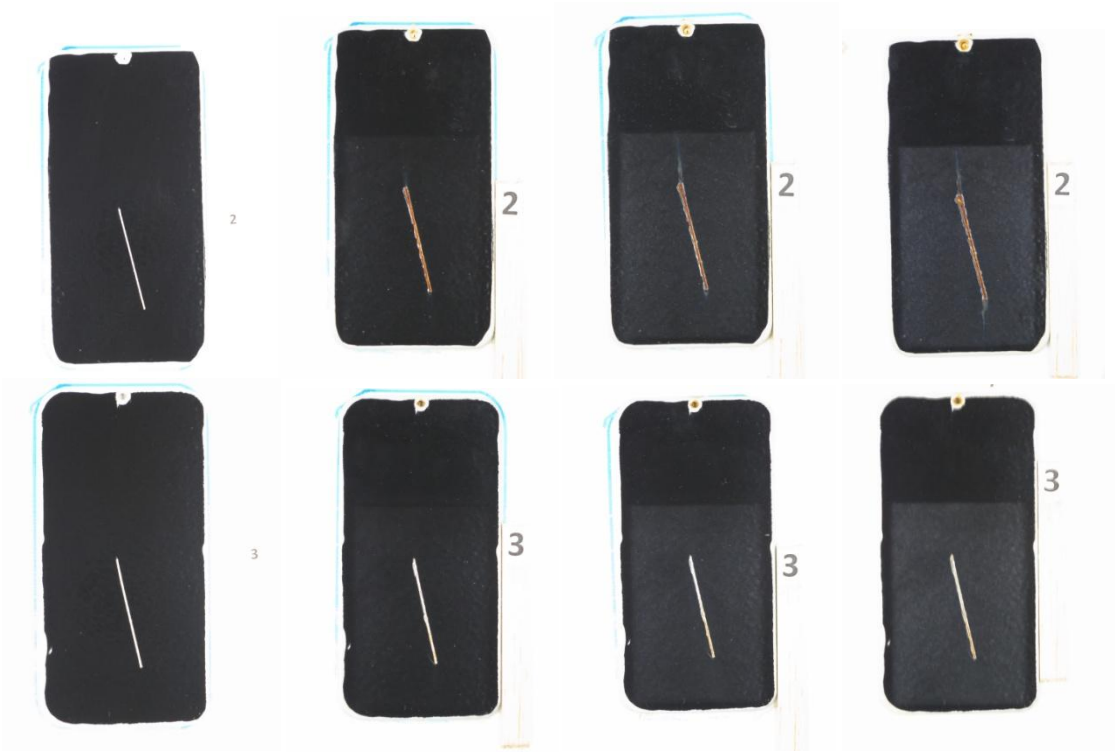


Figure 80: SW-3P Initial, Cycle 9, Cycle 12, Cycle 15

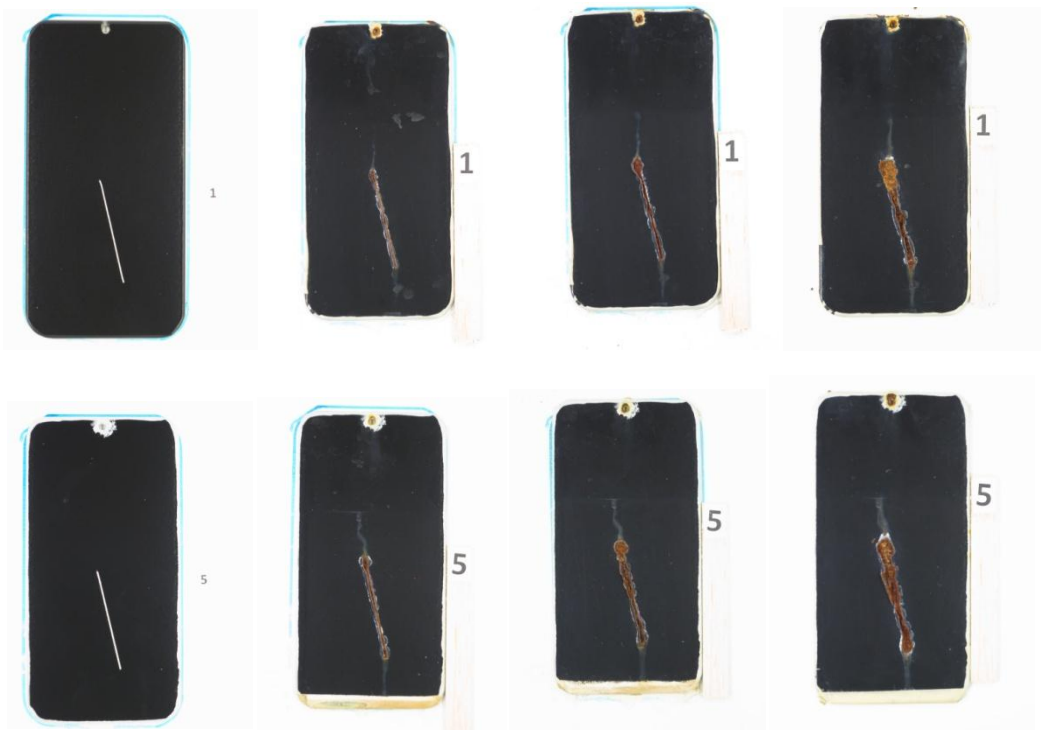


Figure 81: CB-3F Initial, Cycle 9, Cycle 12, Cycle 15

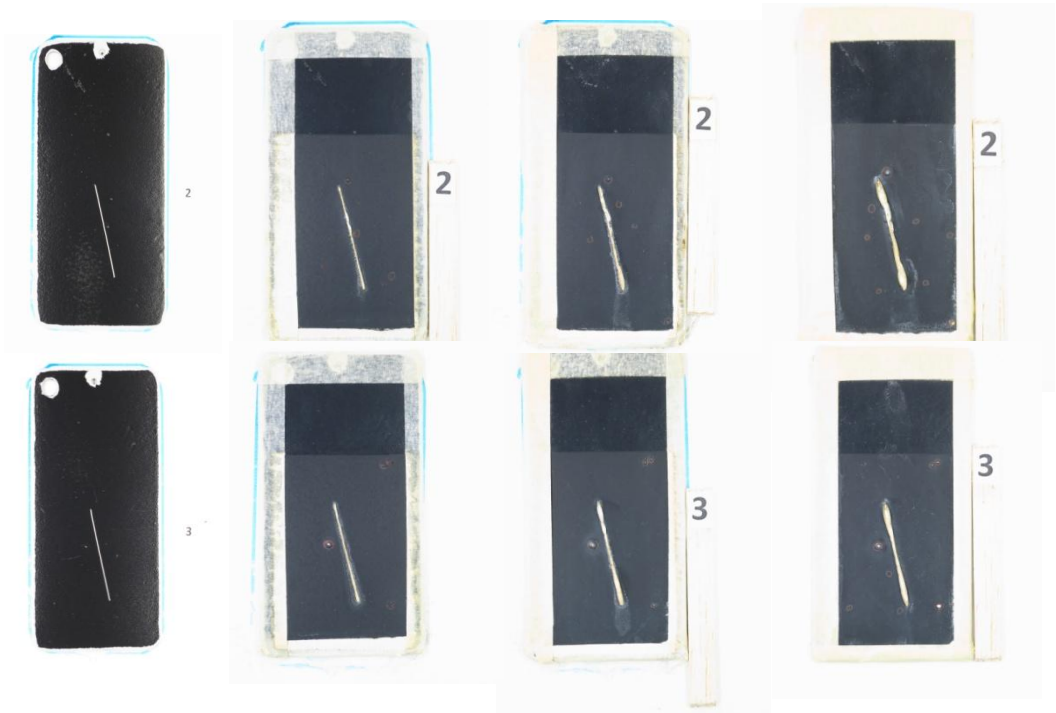


Figure 82: WA-D Initial, Cycle 9, Cycle 12, Cycle 15

Figure 83: CB-D Initial and Final Creepage

Figure 84: SW-D Initial and Final Creepage

Figure 85: SW-3F Initial and Final Creepage

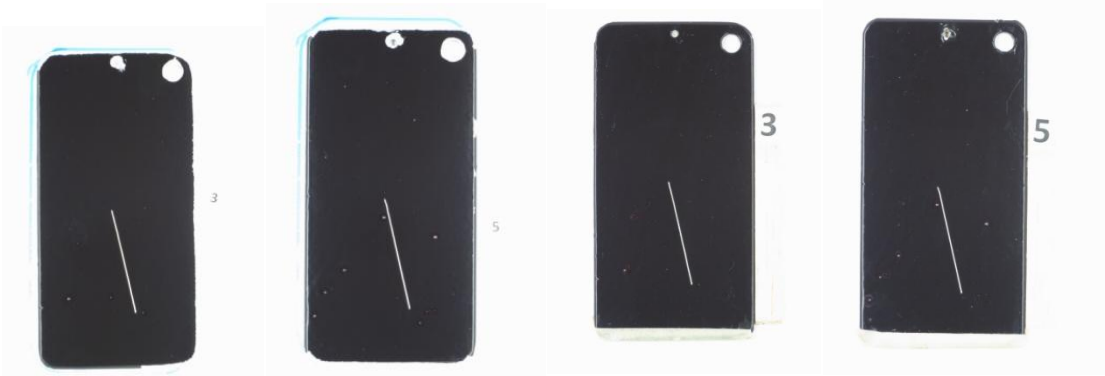


Figure 86: SW-05PD Initial and Final Creepage

Figure 87: SW-04PD Initial and Final Creepage

5.2.1.4 Holidays

Holidays are defects in the coating system that are initially small but can grow to larger sizes with time and exposure to aggressive environments. These defects penetrate through the layers of a coating system down to the galvanized or non galvanized steel substrate. Holidays have adverse effect on the performance of coating systems and it is important to identify and use coating systems that are not susceptible to formation of such defects.

Holidays were measured in all coating systems in this study using both scribed (2 samples per coating system) and un-scribed (3 per coating system) coated samples. Table 15 shows the mean and final number of holidays for each coating system. Figure 88 shows the total number of holidays for all coating systems in this study after the completion of the accelerated weathering test.

The five 3-coat zinc systems in the study (CB-3P, SW-3P, PPG-3P, CB-3F, and SW-3F) experienced the least amount of holidays. Coating system CB-3P was the only system among the five to experience the least level of discontinuities. Overall the 3-coat systems performed the best with regards to protection against holidays. Coating system WA-D was the only coating system of the liquid duplex systems (CB-D, SW-D, WA-D) that experience a significant amount of holidays. All other liquid duplex systems experienced some holidays throughout the testing.

The holidays in the powder coated duplex systems typically occurred at the location of the initial out-gassing craters. At these locations, the craters formed in the top-coat leaving the tie-coat exposed that creates a potential for discontinuities to penetrate deeper into the coating system. Although the out-gassing craters were not holidays initially, they became holidays with exposure to additional cycles of weathering.

Table 16: Final Number of Holidays

Coating System	Total Holidays (5 samples)	Mean Holidays
CB-2	2	0.4
PPG-2	14	2.8
CB-D	8	1.6
SW-D	2	0.4
WA-D	40	8
CB-3P	1	0.2
SW-3P	0	0
PPG-3P	0	0
CB-3F	0	0
SW-3F	0	0
SW-05PD	8	1.6
SW-04PD	20	4

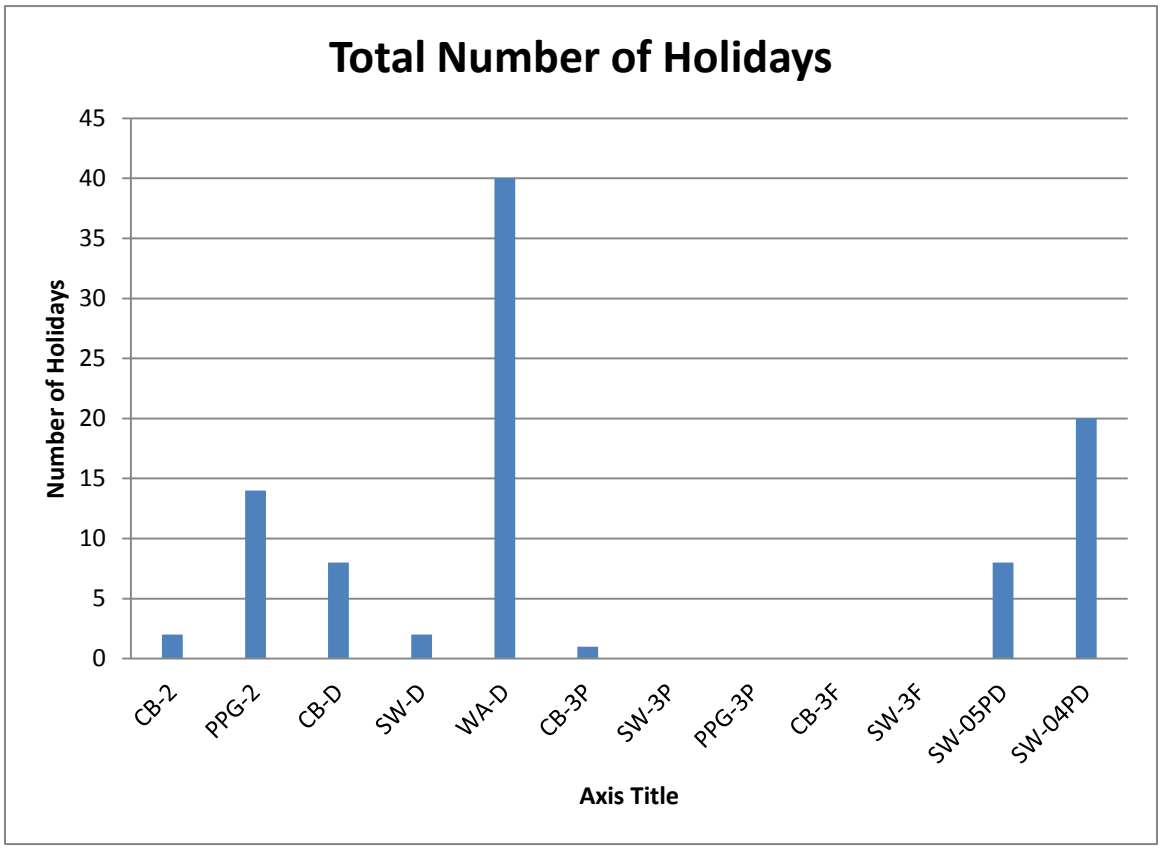


Figure 88: Final Mean Holidays

5.2.1.5 Adhesion Strength

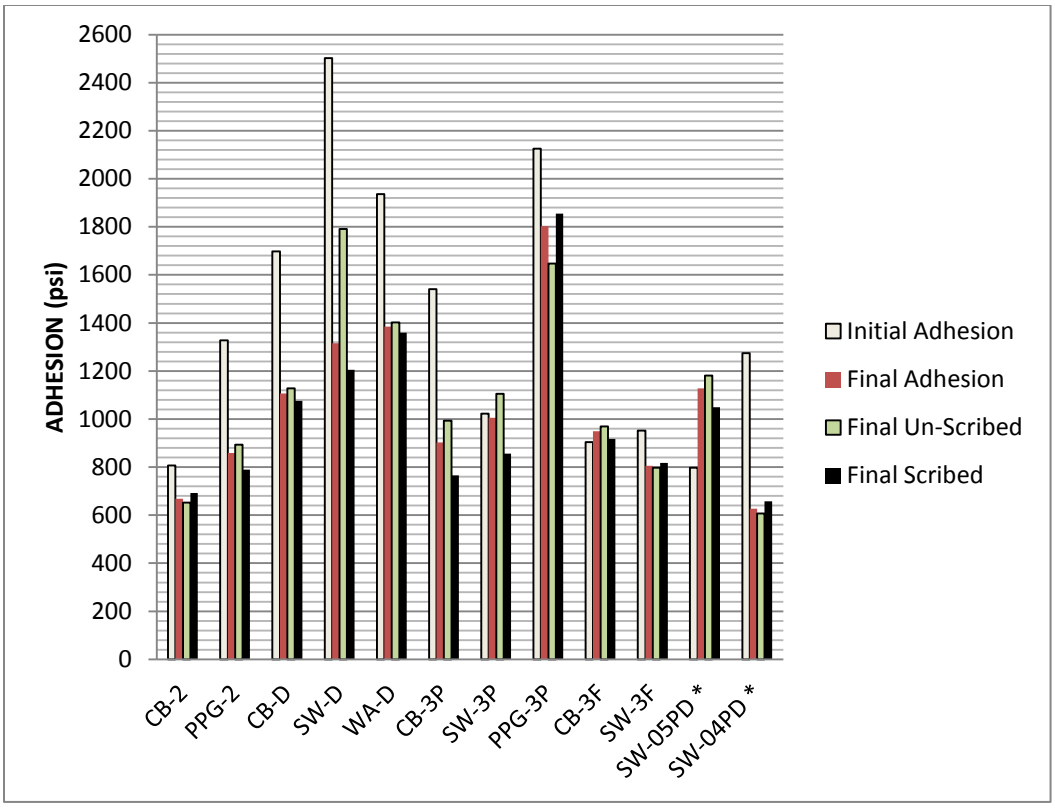
Adhesion tests were conducted as a part of the Freeze/UV/Prohesion testing. Since these tests are destructive in nature they were performed initially on 3 in. x 6 in. un-weathered control samples and on weathered samples at the completion of the weathering test. Two 3”x6” control panels were tested initially for adhesion and pencil hardness. A complete list of all adhesion strength values and types of failures are given in Appendix B.

At the completion of the weathering test, both the scribed (2 samples) and un-scribed (3 samples) samples were tested to determine adhesion strength for all coating systems used in this study. A minimum of three tests were taken on each sample As required by the ASTM standard, adhesion test results were discarded when there was a failure of more than 50% for the bonding epoxy holding the test dolly on the surface of the coated sample. An exception was made for the powder coat duplex systems (SW-04PD and SW-05PD) due to size limitation. Table 16 lists the mean adhesion values for both the control and weathered samples. Figure 89 shows a graphical representation of these values.

Table 17: Initial and Post Weathering Adhesion Values

Coating System	Initial Adhesion (psi)	Final Adhesion (psi)	Final Un-Scribed (psi)	Final Scribed (psi)
CB-2	807	668	652	692
PPG-2	1328	858	893	790
CB-D	1698	1107	1128	1075
SW-D	2502	1315	1791	1205
WA-D	1936	1385	1402	1360
CB-3P	1540	902	993	766
SW-3P	1023	1006	1105	856
PPG-3P	2125	1803	1647	1855
CB-3F	904	949	970	917
SW-3F	952	806	798	818
SW-05PD	798*	1128*	1181*	1050*
SW-04PD	1274*	627	607	657

*Adhesion values of glue failure over 50% included



* Values represented by coating systems SW-05PD had glue failure for initial and final adhesion and values for coating system SW-PD04 had glue failure for initial adhesion

Figure 89: Initial and Post Weathering Adhesion

For the initial and final adhesion tests, all but one of the non-galvanized 2- and 3-coat systems experienced a primarily inner coat cohesion failure within the zinc primer. This zinc cohesion failure occurred in the following systems: CB-2, PPG-2, CB-3P, and SW-3P. The coating system PPG-3P was the only non-galvanized system that experienced cohesion failure within the polyurethane top-coat, and subsequently had a higher adhesion strength than the coatings that experienced cohesion failure of the zinc primer From the results of these tests, it was found that the weakest adhesion strength, or the controlling value, was obtained when the failure occurred in the zinc-rich primer for both the initial and final adhesion values. Figures 90 and 91 show photographs of the initial cohesion failure of the top-coat and the final cohesion failure of

the mid-coat, respectively, for coating system PPG-3P. An example of cohesion failure of the zinc coating is shown by the photographs in Figure 92.

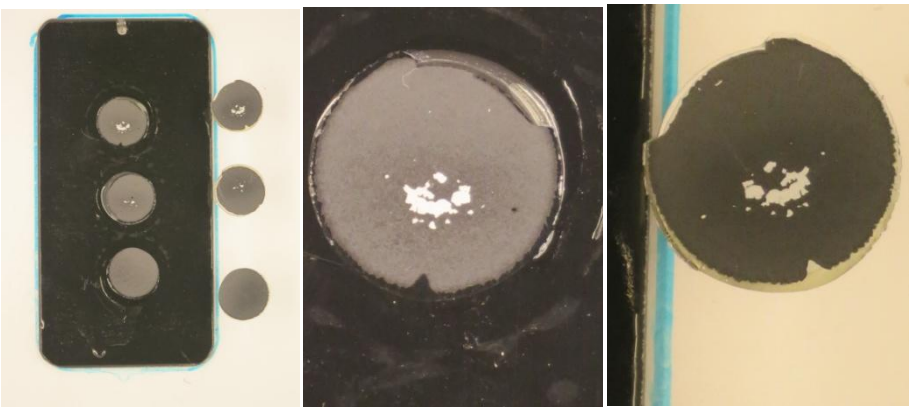


Figure 90: Initial Cohesion Failure of Top-Coat (PPG-3P)

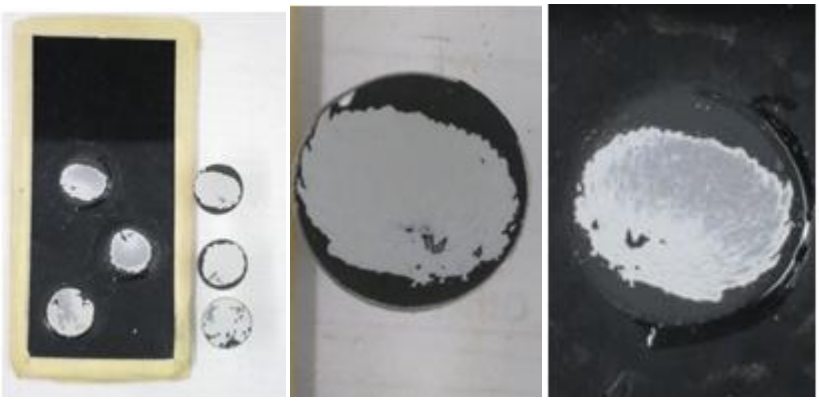


Figure 91: Final Cohesion Failure of Mid-Coat (PPG-3P)

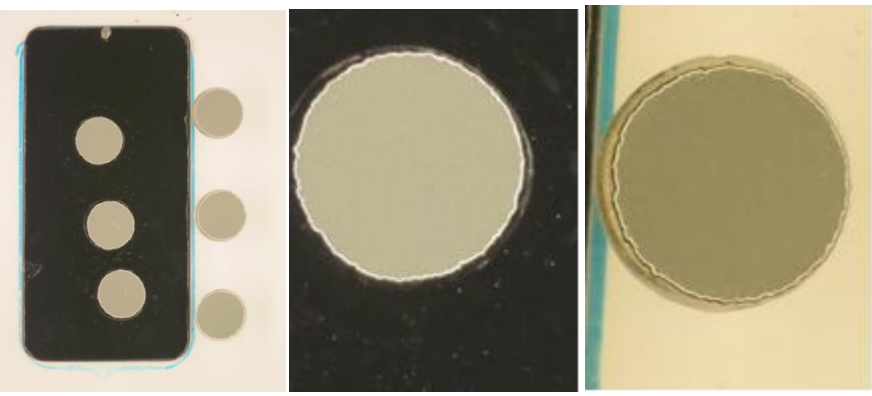


Figure 92: Initial Cohesion Failure of Zinc Coating (SW-3P)

An evaluation of the results of this study showed that the duplex liquid coating systems achieved higher initial and final adhesion strength values than all the non-galvanized systems except with the exception of PPG-3P. The results of this study showed that with proper galvanization, surface preparation, and application techniques adequate adhesion strength may be achieved in the duplex coating systems. It was found that in most cases a higher adhesion strength can be achieved for duplex systems compared with organic zinc-rich coating systems. Coating system WA-D experienced cohesion failure in the tie-coat for both the initial and final adhesion tests. CB-D initially experienced cohesion failure of the top-coat, and for the final test it experienced a cohesion failure of the tie-coat. Coating system SW-D experienced a combination of cohesion failure of the top-coat and an adhesion failure of the tie-coat to the galvanized substrate for its initial adhesion. Final adhesion failure for coating system SW-D were generally adhesion failure of the tie-coat to the substrate. Photographs in Figure 93, from left to right, show the initial adhesion tests for coating system CB-D, WA-D, and SW-D. Figure 94 shows photos for the final adhesion failure values of these coating systems.

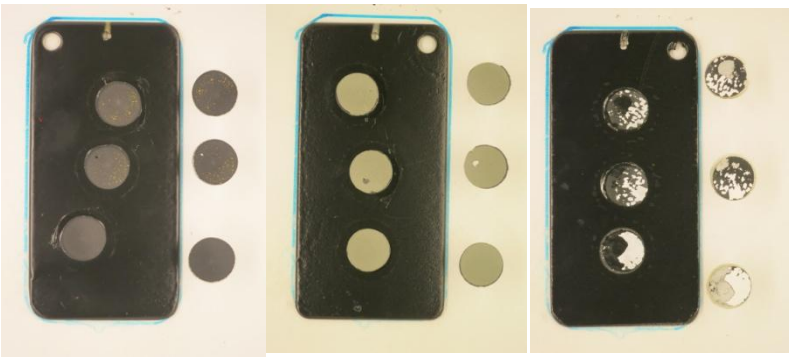


Figure 93: Initial Adhesion Test (CB-D, WA-D, SW-D)

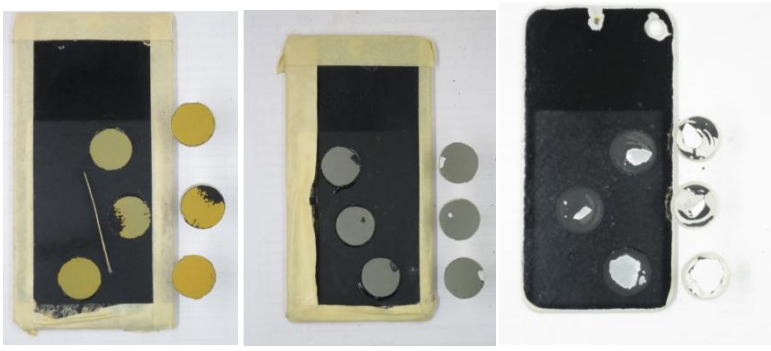


Figure 94: Final Adhesion Tests (CB-D, WA-D, SW-D)

It was found for powder coating duplex systems SW-05PD and SW-04PD that the observed adhesion strength failure occurred in the epoxy bonding film at the interface of the dolly's base and the coating surface. However, the adhesion strength due to this failure was still larger than the minimum criteria. Figure 95 includes photographs for the initial epoxy bonding failure of the test dolly for coating systems SW-05PD and SW-04PD. Figure 96 shows a photograph of the final adhesion failure of the top-coat to the tie-coat for coating system SW-04PD.

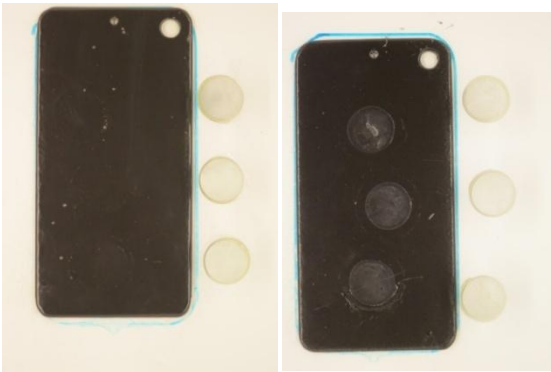


Figure 95: Initial Glue Failure (SW-05PD and SW-04PD)

Figure 96: Final Adhesion Failure SW-PD04

Coating systems CB-2, PPG-2, CB-D, WA-D, SW-D, CB-3P, SW-3P, PPG-3P, and SW-3F all experienced a reduction in the final adhesion strength taken after the accelerated weathering tests. Even with the reductions in the adhesion strength after the completion of the weathering test, all of these coating systems still met the minimum adhesion criteria. In general, the duplex liquid coating systems had a greater percent of decrease in the adhesion strength values when compared to the 2- and 3-coat coating systems. However, liquid duplex systems still achieved higher final adhesion values than all other 2- and 3-coat systems except system PPG-3P. Figure 97 shows the difference for initial and final adhesion values for all the coating systems except the powder coated system. Figure 98 shows the percent change from initial adhesion to final adhesion.

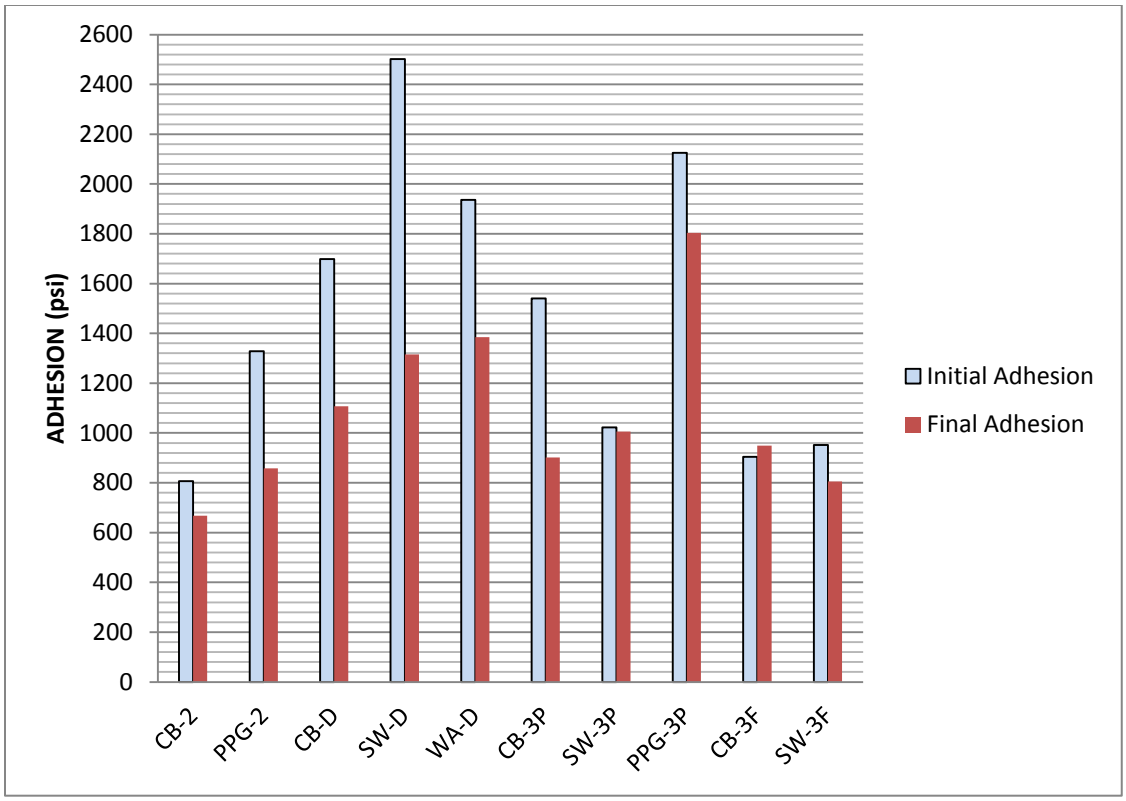


Figure 97: Initial vs. Final Adhesion Values

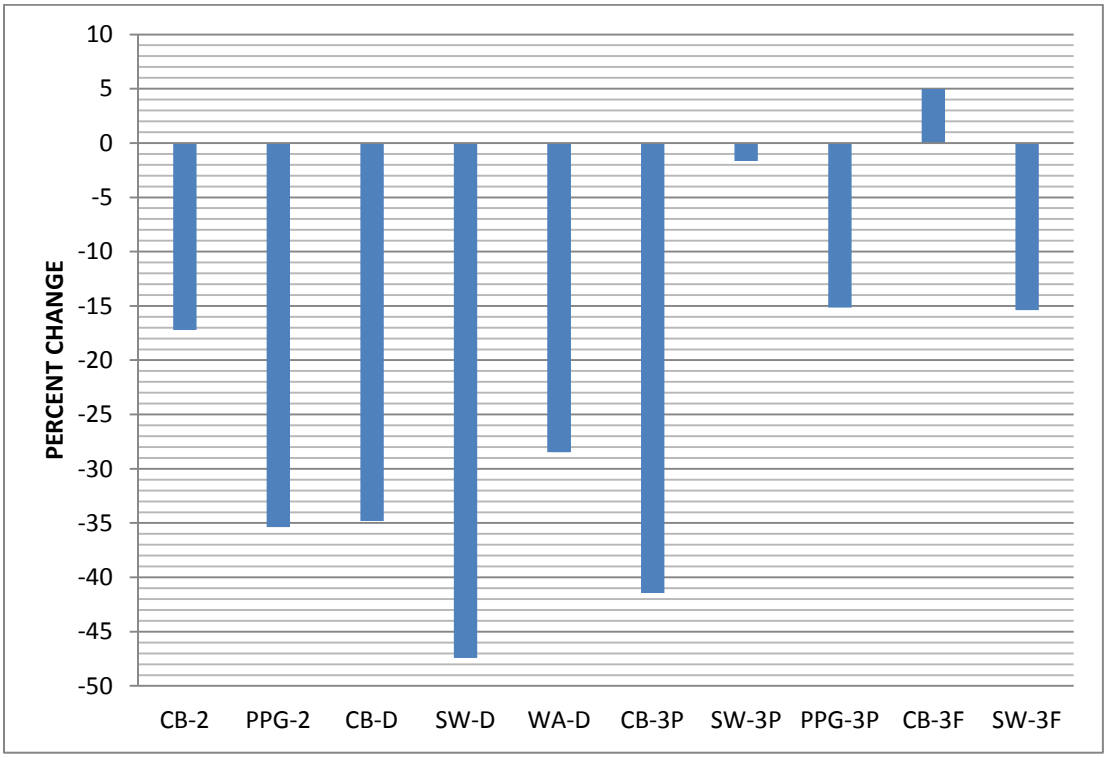


Figure 98: Percent Change in Adhesion

5.2.1.6 Flexibility

The flexibility performance of the coating systems included in this study was measured on two 4 in. x 6 in. control samples and on two weathered samples. To determine the level of flexibility of a coating system, the percentage of the elongation of each coating system was measured by means of mandrel bending test. Table 17 shows the initial and final percent elongation of all coating systems evaluated in this study. Samples were weathered for 13 cycles instead of 15 due to the presence of excessive rusting on edges of the panels. The excessive rusting of the edges is attributed to the small thickness of the plate samples as required for the mandrel bend testing device. Coating system CB-2 experience significant rusting on the edges leaving the samples unusable for the final bending tests.

The duplex liquid coating systems (SW-D, CB-D, WA-D) had the highest initial percent elongation from the control samples compared with the other coatings. This is most likely attributed to the absence of a zinc primer. When conducting mandrel bending test after the completion of the accelerated weathering experiment, one half of the coating systems in the study (CB-2, PPG-2, SW-3p, PPG-3P, SW-3F, SW-04PD, SW-05PD) developed cracks that extended for the entire width of the test panels. Accordingly, these coating samples were classified as having zero elongation.

Table 18: Percent Elongation

Coating System	Initial Percent Elongation	Final Percent Elongation
CB-2	22	NA
PPG-2	16	0
CB-D	37	24
SW-D	33	6
WA-D	28	27
CB-3P	10	12
SW-3P	24	0
PPG-3P	12	0
CB-3F	13	8
SW-3F	17	0
SW-05PD	0	0
SW-04PD	15	0

5.2.1.7 Pencil and Scratch Hardness

Pencil and scratch hardness tests were performed for all coating systems in the study, initially on two control samples and later on three samples at the completion of the accelerated weathering test. The pencil hardness test is done with the hardest pencil that will not cut into the coating, and the scratch hardness test is performed with the hardest pencil that will not scratch the coating. The appropriate pencil hardness for each test is determined by starting with a soft pencil and continuing the tests with gradual increase of pencil hardness. Table 18 lists the pencil and scratch hardness results for each of the coating system included in this study. It was found that there was not a significant change in the pencil and scratch hardness values for the coating systems when obtained before and after the completion of the accelerated weathering test.

Table 19: Pencil Scratch Hardness

Coating System	Initial Pencil	Final Pencil	Initial Scratch	Final Scratch
CB-2	2H TO 3H	3H	F	F
PPG-2	3H to 4H	3H to 4H	HB TO F	F
CB-D	3H	3H to 4H	F	F
SW-D	2H TO 3H	3H	HB to F	F
WA-D	5H	5H	2H	H to 2H
CB-3P	3H	3H to 4H	F TO H	F
SW-3P	2H TO 3H	3H	HB TO F	F
PPG-3P	F	F to H	B	HB
CB-3F	2H	2H	HB	HB
SW-3F	2H	2H to 3H	HB	HB
SW-05PD	5H	5H	B	HB
SW-04PD	5H	5H to 4H	8B Still Leaves Mark	B

5.2.1.8 Degree of Rusting and Blistering

Samples for all coating systems in the study were examined after each cycle of accelerated weathering test to determine the extent of rusting and blistering. No coating system exhibited rusting of the substrate. Only one coating system (SW-04PD) showed evidence of blistering with a size "No. 6" and a frequency of "medium."

5.2.1.9 Freeze/UV/Prohesion Regression Analysis

A linear regression analysis was conducted on the results of the accelerated weathering test to explore possible correlations among the various performance parameters for coating samples that were included in this study. The considered performance parameters included: changes in color and gloss, rust creepage, holidays, and adhesion strength. Table 19 includes a list of regression parameters and their respective R^2 values. It should be noted that the analysis excluded coating system SW-04PD for the initial adhesion strength and system SW-05PD for both the initial and final adhesion strength due to bonding epoxy failure at the interface of the test dolly and the coating surface.

Considering the results shown in Table 19, it can be concluded that there was no strong correlation existed between any two performance parameters that were included in this study. A low R^2 value (0.155 or less) was obtained for the regression analyses that were performed in the study.

Table 20: Freeze/UV/Prohesion Regression Analysis

Regression Variables	Linear Regression (R^2)
ΔE vs. % Decrease in Gloss	0.009
ΔE vs. Rust Creepage	0.155
ΔE vs. Holidays	0.073
ΔE vs. Initial Adhesion	0.000
ΔE vs. Final Adhesion	0.048
% Decrease in Gloss vs. Rust Creepage	0.006
% Decrease in Gloss vs. Holidays	0.393
% Decrease in Gloss vs. Initial Adhesion	0.378
% Decrease in Gloss vs. Final Adhesion	0.221
Rust Creepage vs. Holidays	0.000
Rust Creepage vs. Holidays (Non-Duplex)[1]	0.366
Rust Creepage vs. Initial Adhesion strength	0.094
Rust Creepage vs. Final Adhesion strength	0.008
Holidays vs. Initial Adhesion strength	0.080
Holidays vs. Final Adhesion strength	0.005

[1] Duplex coating systems excluded

5.2.2 Xenon Arc Testing

Xenon Arc testing was conducted on all top-coats used in this study to consider the effect of longer wave radiations on coatings' color retention and the effect on changes in color when different colors (black vs. blue) were used.

Coated samples were tested for 15 weekly cycles for federal color (27038) black and federal color (15092) blue. A comparison between the changes in color (ΔE) for the black and blue samples is shown in Figures 99 and 100. It was found that almost all samples with color

blue exhibited a greater color change value (ΔE) when subjected to Xenon Arc light exposure. The exception was for coating system SW-04PD with a possible effect from the anti out gassing agent that produced a paraffin film on the surface.

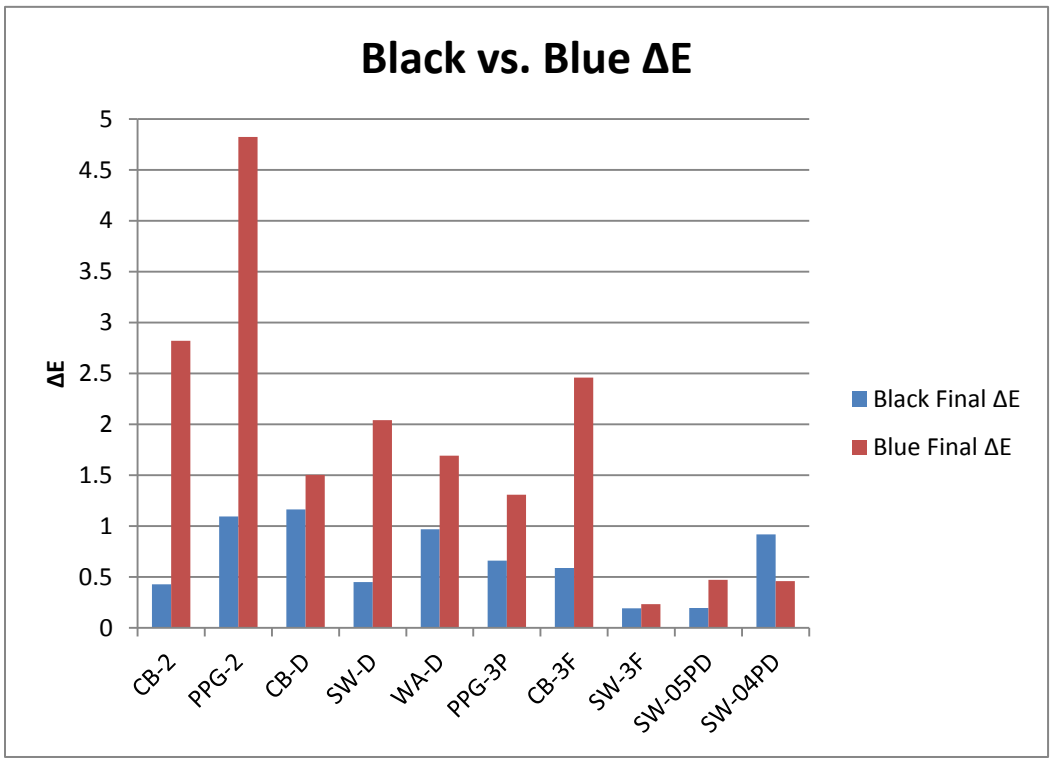


Figure 99: Final Black vs. Blue ΔE

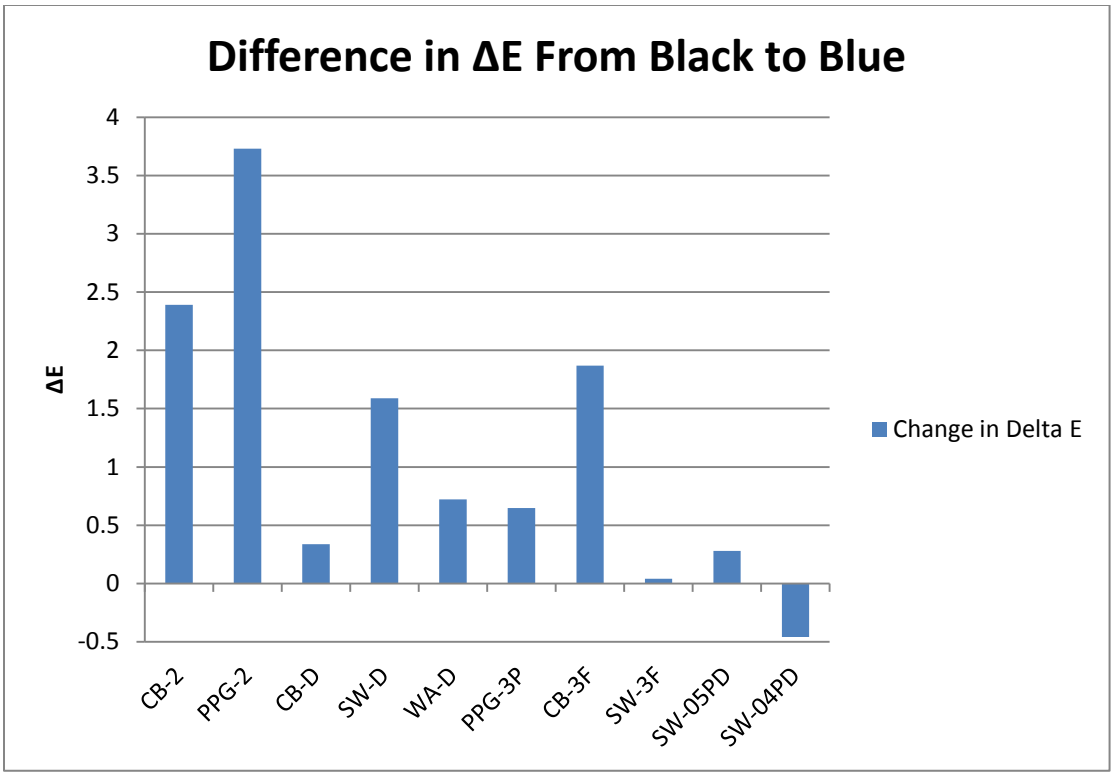


Figure 100: Change in ΔE from Black to Blue

Some coating systems, (i.e., PPG-2) exhibited color fading for blue samples after the completion of fewer weathering test cycles when compared with black samples for the same coating system. Figures 101 and 102 show photographs of blue and black PPG-2 samples, respectively, for the initial state and after the completion of weathering test cycles 5, 9, 12,and 15. The calculated ΔE values for the blue samples were found to be significantly higher than those for black samples of the same coating system. In addition, the appearance of color fading is less prominent when darker colors are used.

Figure 101: Xenon PPG-2 Black Samples (Initial, 5, 9, 12, 15)

Figure 102: Xenon PPG-2Blue Samples (Initial, 5, 9, 12, 15)

Changes in color (ΔE) for black samples subjected to the Xenon Arc test were found to be primarily a function of ΔL. The finding is similar to those obtained for black samples subjected to the accelerated weathering test, as shown earlier in this report. Figures 103 and 104 show the measured values of ΔE vs. ΔL and the results of a regression analysis for these two parameters, respectively, for all coating systems used in this study. Close agreement can be seen between the two parameters as it is supported by the calculated high correlation coefficient (R^2=0.968) as shown in Figure 104. For blue samples the change in a color from blue to yellow is represented by the b value in the CIELAB color indexing system. Here, the ΔE values for blue samples are primarily a function of the absolute Δb values. As shown in Figures 105 and 106, there is a strong correlation between the change in color (ΔE) and the absolute Δb value (R^2=0.847).

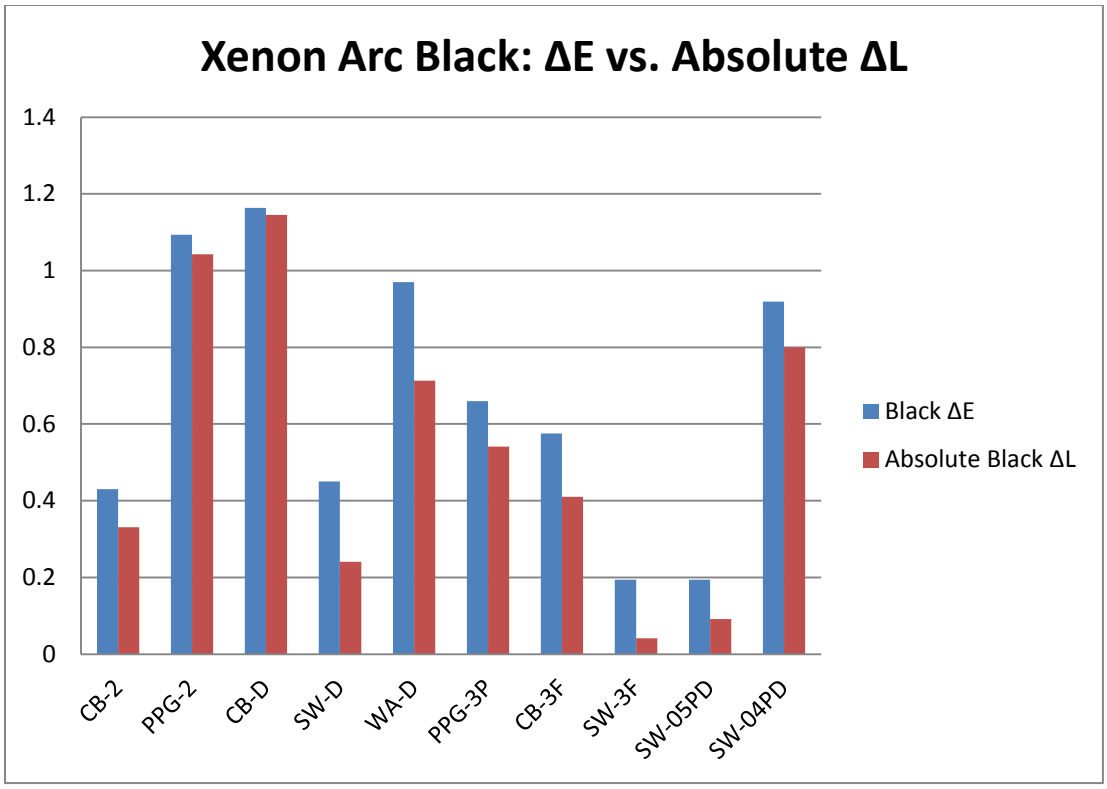


Figure 103: Xenon Arc Black: ΔE vs. ΔL

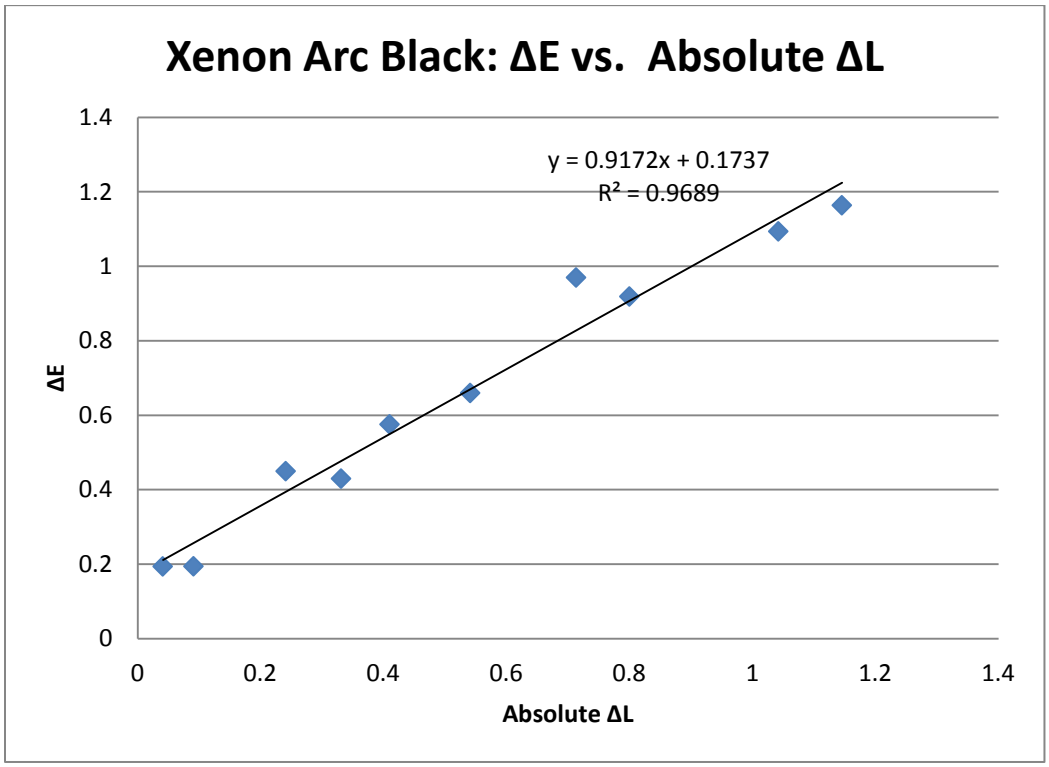


Figure 104: Xenon Arc Regression Black: ΔE vs. ΔL Absolute

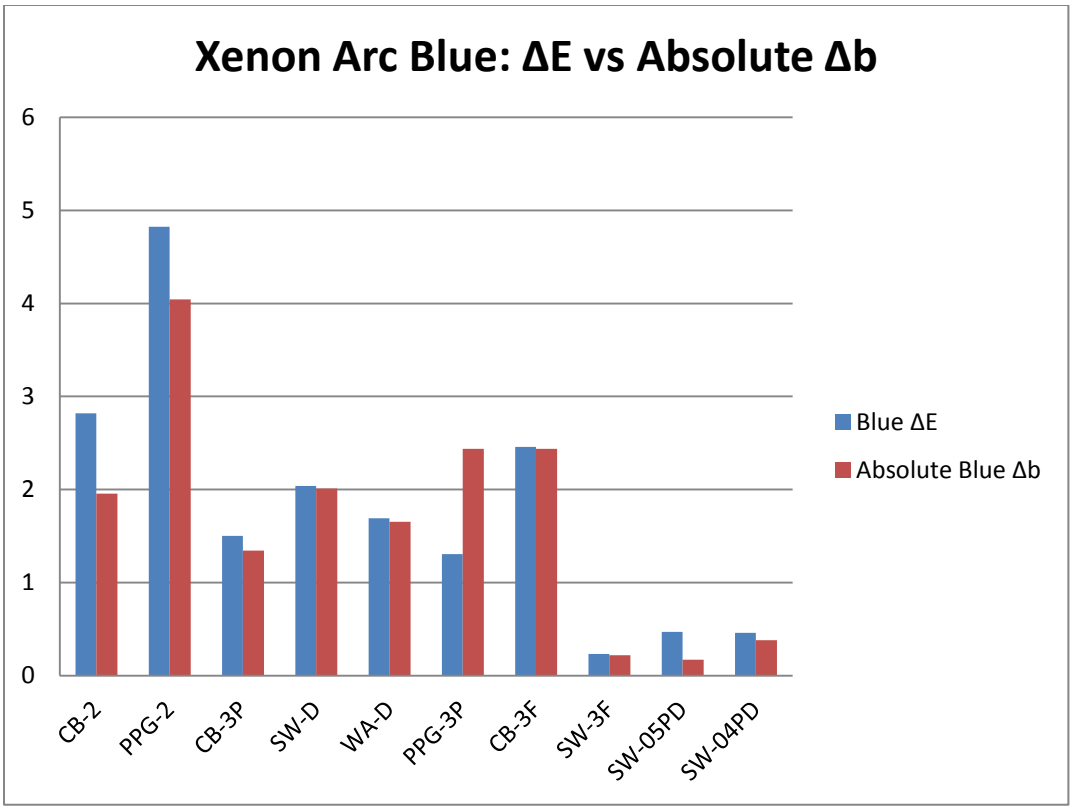


Figure 105:Xenon Arc Blue: ΔE vs. Absolute Δb

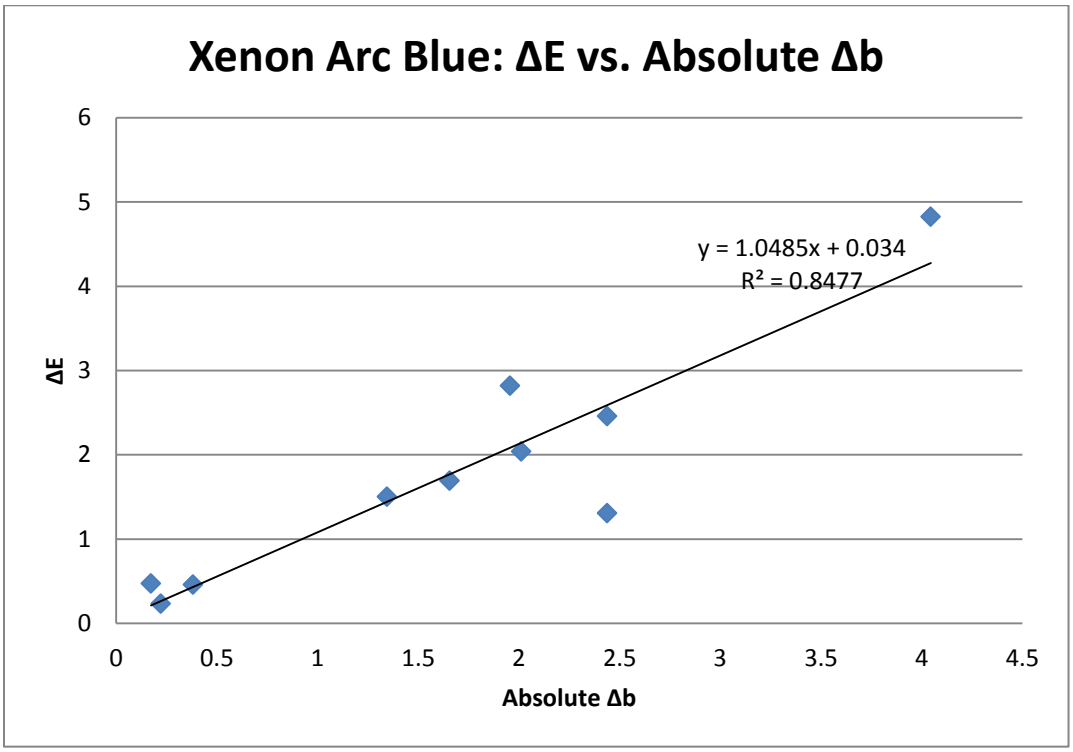


Figure 106: Xenon Arc Regression Blue: ΔE vs. Absolute Δb

5.2.2.1 Regression Analysis: Xenon Arc Testing - Blue vs. Black Samples

A regression analysis was conducted to explore the possibility of existence of a correlation between ΔE values for blue color and those for black color. As shown in Figure 107, no correlation can be seen to exist when the Xenon Arc test is conducted for the samples with these two colors. Additional experiments will need to be performed on different colors to find a possible color related correlation.

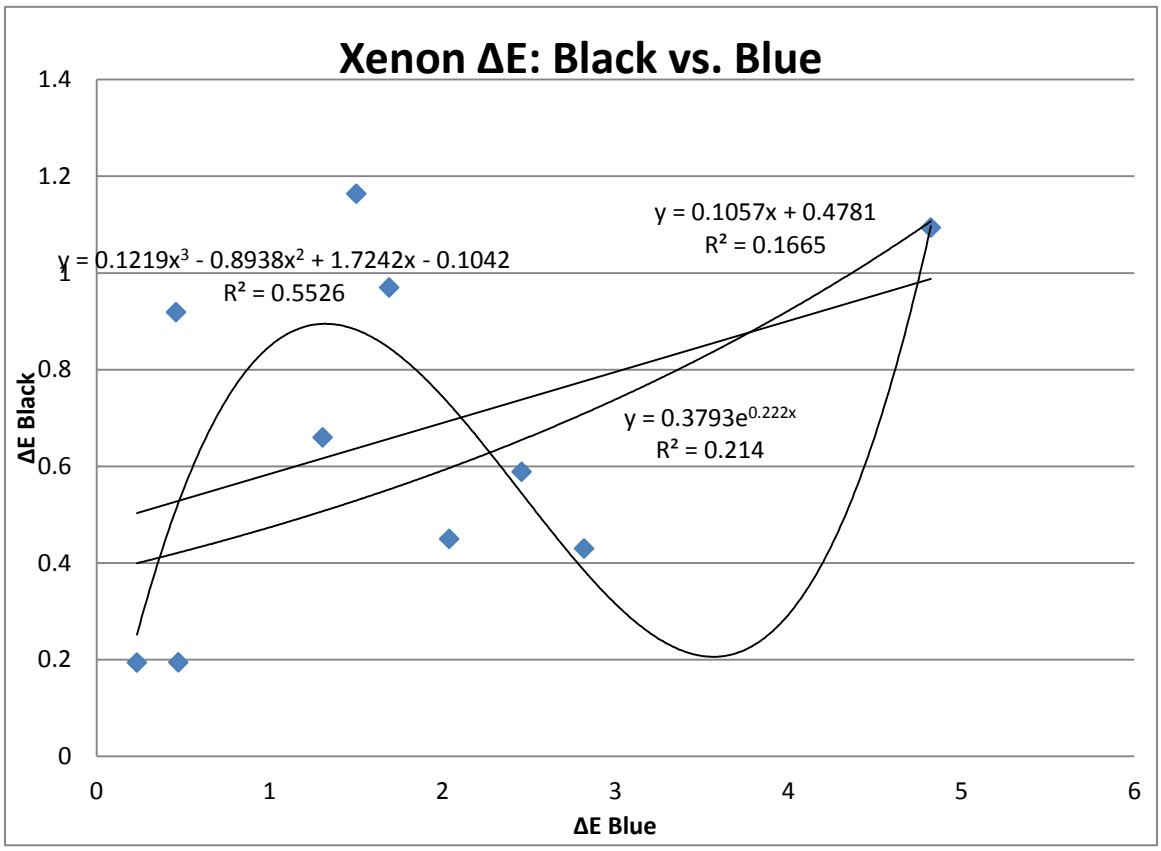


Figure 107: Regression Analysis Xenon: ΔE Black vs. ΔE Blue

5.2.2.2 Regression Analysis: Prohesion vs. Xenon Arc Tests for Black Samples

A regression analysis was completed to explore the possibility of existence of a correlation between color changes in black coated samples for the Freeze/UV/Prohesion testing

and the Xenon Arc testing. The analysis was also performed for the gloss retention properties under the same test conditions.

Both linear and exponential fit regression analyses were performed for color retention under the two testing programs. Figure 108 shows the resullts of the analyses where no significant correlation can be noticed. When results for color changes in coating systems WA-D and CB-D were removed (outliers in the color change results when compared with other systems) from the regression analyses, a somewhat better correlation results were obtained, see Figure 109. Additional experimental studies will be required to achieve results that offer higher certainties.

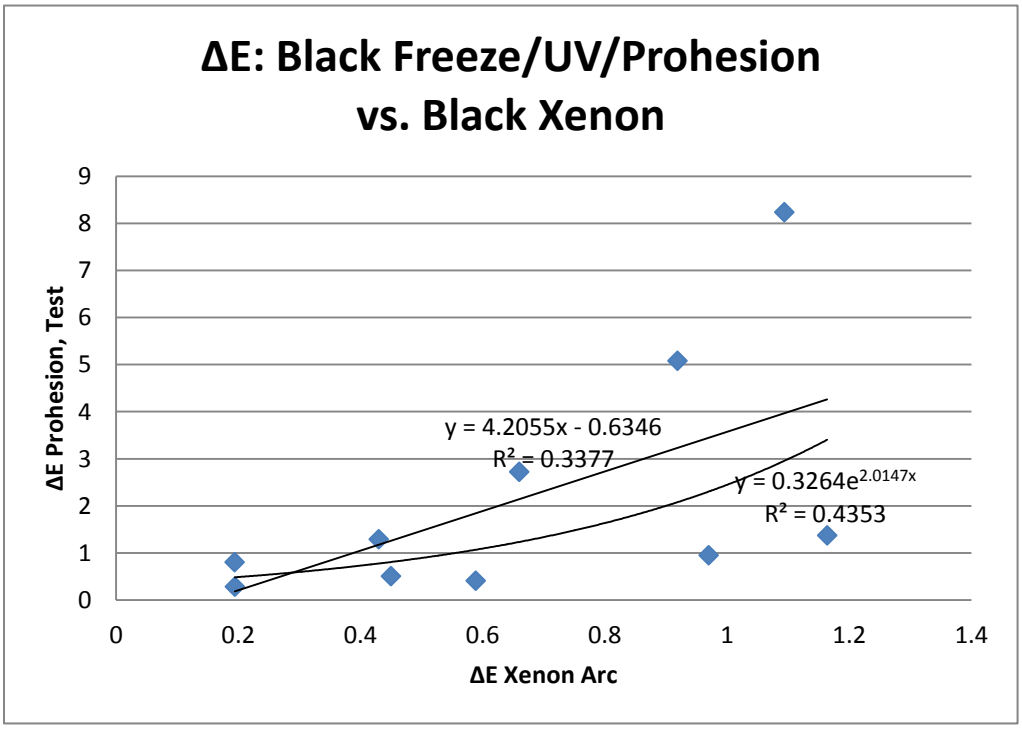


Figure 108: Regression Analysis: ΔE Freeze/UV/Prohesion Test vs. ΔE Xenon Arc Test

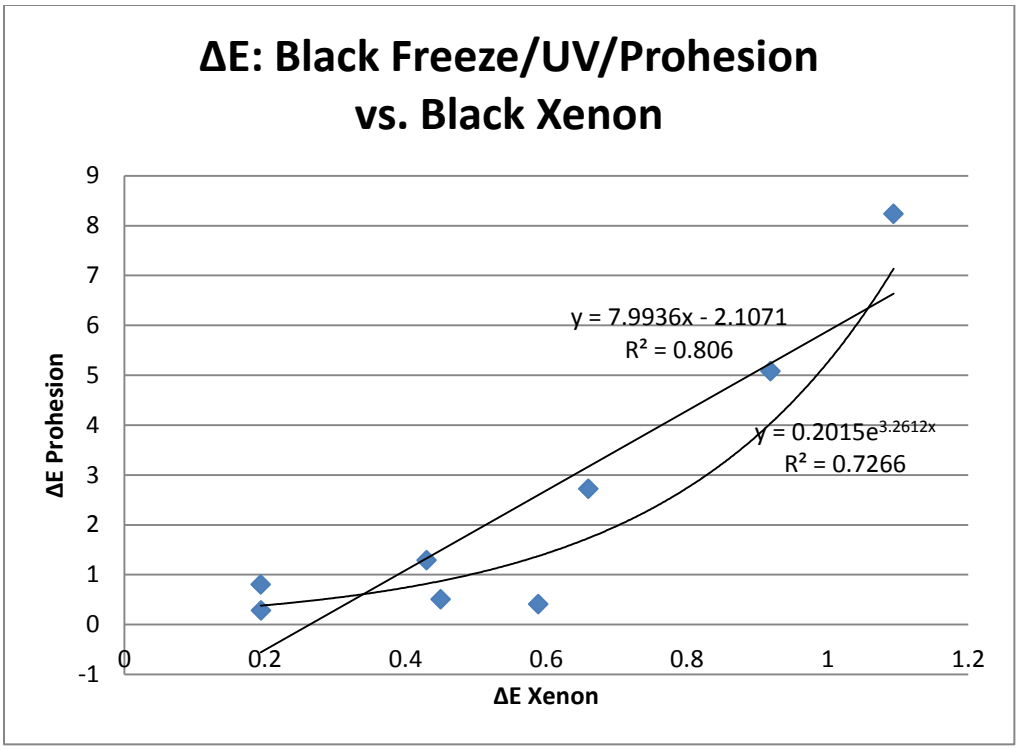


Figure 109: Regression Analysis: ΔE Freeze/UV/Prohesion vs. ΔE Xenon, Excluding WA-D and CB-D

Linear and exponential fit regression analyses were also performed on the gloss retention properties of black samples subjected to Freeze/UV/Prohesion testing and Xenon Arc testing. Figure 110 shows the results of the analyses that indicate a somewhat strong correlation (R^2 = 0.846) between the loss of gloss values for black samples under the two test programs. If this finding can be supported by additional experiments on different colors, it will be possible to determine color retention capability of different color top-coats with a simpler, less costly, and less time consuming test such as the Xenon Arc test.

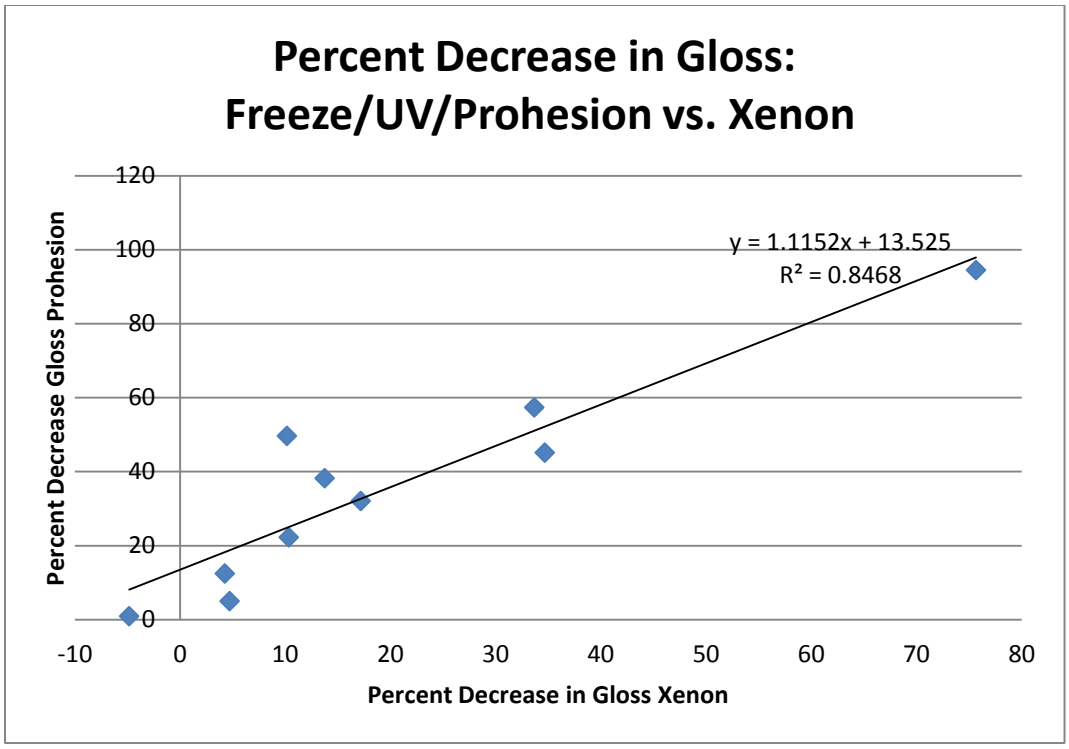


Figure 110: Linear Regression: Decrease in Gloss Freeze/UV/Prohesion vs. Xenon

5.3 Cost Analysis

The overall cost of a coating system is normally an important factor in its final selection for application to bridge railings and structures. There are several factors that influence the overall cost of a coating system. These include the cost of material, number of required coats, type of coating system, type of required surface preparation (SP-10, or SP-6), type of application (spray of brush), and location of the application (shop vs. field).

Material costs vary depending on the location and size of a project. Accordingly, considering only the material cost by volume or weight may not offer the best representation of the actual cost for a project. To include the effects of the influencing factors into material cost, a 2008 publication by the National Association of Corrosion Engineers (NACE) used the results of a cost survey from coating manufacturers, steel fabricators, contractors, galvanizers, and end users to establish an average cost and service life of generic coatings systems (53). These average costs were used to arrive at an approximate cost for various coating systems that were used in this study, see Table 20. An Inflation factor of 7.5% was taken into account in accordance to the United States Bureau of Labor and Statistics' data (54).

As shown in Table 20, the total cost of all materials for 2-coat systems is comparable to that for 3-coat coating systems. However, when application costs are considered, the cost of a 2-coat system becomes less due to the smaller labor cost associated with the application of one fewer coat. Table 21 shows surface preparation costs along with application costs for different coating systems. Shop application costs were used in all cost calculations in the NACE publication. Surface preparation process of SSPC-10 is used for steel surface and SSPC-6 is used as a substitute for SSPC-16 for galvanized surface preparation since no cost data was provided for SSPC-16 in the NACE publication. When surface preparation and application costs are considered, the 3-coat polyurethane and duplex systems have an approximately 15% higher cost

than that for 2-coat systems. The cost of a 3-coat fluoropolymer system is approximately 25% higher than the cost of a 3-coat polyurethane system and 45% more than that for a 2-coat system.

The total costs of installed coating systems that were included in the testing program for this study are shown in Table 22.

Table 21: Material Cost of Coatings per Square Foot

Coating System	Primer Coat / DFT(mils)	Material Cost Primer	Mid-Coat / DFT(mils)	Material Cost Mid	Top-Coat / DFT(mils)	Material Cost Top
2-Coat Polysiloxane	Organic Zinc/3	$0.44	NA	$0.00	Siloxane Epoxy/4	$0.62
3-Coat Polyurethane	Organic Zinc/3	$0.44	Epoxy Mid/4	$0.27	Polyurethane Aliphatic HB Acrylic/3	$0.44
3-Coat Fluoropolymer	Organic Zinc/3	$0.44	Epoxy Mid/4	$0.27	Polyurethane Fluorinated /2.5	$1.67
Duplex- Epoxy	Galvanization[1]	$1.89	Epoxy Mid/ 4	$0.27	Polyurethane Aliphatic HB Acrylic/3	$0.44

[1]Includes labor, equipment, surface preparation, and related costs

Table 22: Surface Preparation and Application Costs per Square Foot

Coating System	Surface Preparation	Application Primer Cost	Application Mid Coat Cost	Application Top-Coat Cost
2-Coat Polysiloxane	$1.90[1]	$0.57	$0.00	$0.58
3-Coat Polyurethane	$1.90[1]	$0.57	$0.55	$0.58
3-Coat Fluoropolymer	$1.90[1]	$0.57	$0.55	$0.58
Duplex- Epoxy	$1.01[2]	$0.00	$0.55	$0.58

[1]SP-10 Conventional with Expendable Abrasives

[2]Use SP-6 Conventional with Expendable Abrasives as substitute for SP-16 Brush off Blast

Table 23: Final Costs per Square Foot

Coating System	Final Material Cost	Total Cost [1]
2-Coat Polysiloxane	$1.06	$4.11
3-Coat Polyurethane	$1.15	$4.75
3-Coat Fluoropolymer	$2.38	$5.98
Duplex- Epoxy	$2.60	$4.74

[1]Cost includes: surface preparation, application, and materials costs

Service life for coating materials should be considered in order to arrive at an effective cost for each coating system. Service life for conventional coating systems is defined as "the time from installation until the occurrence of 5 to 10% coating break down (SSPC-Vis 2 Grade 4), and until an active rusting of the substrate is present" (53). It must be noted that this definition of service life has been specified for full coating replacement and it does not consider aesthetics degradation, such as color fading, in a coating system. Service life for duplex systems has been shown to improve by a factor of 1.5 to 2.3 over that for galvanized or painted structures alone (16). This is primarily due to the reduction of corrosion from the enhanced benefits of combining galvanization and painting options. The type of environmental exposure also plays an important role on the service life of various coating systems. Table 23 shows the average service life for the specific coating systems that were included in this study (16)(53). It is shown that duplex systems can have a significantly longer service life than conventional 2- and 3-coat systems. For highway bridge environments, service life is considered under the "Severe / C5 exposure" category.

Table 24: Coating Systems Practical Service Life

	Practical Service Life Years	
Coating System	Moderate (Industrial) / C3	Severe (Heavy Industrial) / C5
2- Coat Moisture Curing Urethane Zinc / Polyaspartic	21	15
3- Coat Polyurethane (Inorganic Zinc / Epoxy / Polyurethane)	21	15
3- Coat Fluoropolymer (Epoxy Zinc / Epoxy / Fluorinated Polyurethane)	22	17
Duplex Liquid (Galvanized / Epoxy / Urethane)	84	-

Life cycle cost for coating systems should also be considered over the service life. Life cycle cost takes into account maintenance painting to extend the time needed for full repainting of the structure. An investigation by Helsel (16) considered the life cycle cost of zinc-rich coatings and galvanized duplex systems in Moderate / C3 exposure environments and showed that duplex systems had the lowest life cycle cost than 2-coat polyaspartic and 3-coat polyurethane coating systems. It was shown that 2-coat systems had a lower life cycle cost than the 3-coat systems mainly because of the reduced initial application costs.

5.4 Coating Rankings

Coating systems included in this study have been ranked based on their overall performance. The ranking of the coating systems were based on an acceptance pass/fail criteria and a weighted average of overall performance according to various evaluated parameters in this study. The initial pass/fail criteria for each coating system was based on meeting a minimum accepted adhesion value. If a coating system did not achieve this value, it was considered a "fail" and excluded from further consideration for ranking. A minimum adhesion value of 600 psi was used as an acceptance value for all coating systems. This value has been recommended by NEPCOAT as a minimum acceptance for organic zinc coatings (18).

Coating systems that met the adhesion test, were ranked based on the following performance evaluation parameters: change in color (ΔE), percent change in gloss, rust creepage, and mean holidays. Table 24 details the weighted average that was used for the performance evaluation parameters in ranking of the coating systems. Since the emphasis of this study is on the aesthetic of the coating systems for bridge railings, a larger weight has been assigned to this parameter.

Table 25: Evaluation Parameters Weighted Average

Evaluation Parameters	Change in Color (ΔE)	% Change in Gloss	Rust Creepage	Mean Holidays	Total
Weighted Average	0.45	0.25	0.15	0.15	1

Prior to taking the weighted average, the ranking of each coating system was made by assigning a value of 0 (poor) to 10 (exceptional) to each coating system based on performance in each of the four evaluation parameters shown in Table 24. After taking the weighted average for each performance evaluation parameter, the coating systems were ranked from 1 (top performer) to 12 (lowest performer).

To establish the 0 to 10 score for each evaluation parameter, a "perfect" value (score of 10) was assigned for exceptional/perfect performance and a calculated value was used for the poor performance (0 score). For example, when considering the evaluation parameter of "holidays," the best performing system exhibited no holidays and accordingly received a perfect score of 10. The number of holidays on a coating resulting in a poor performing (score of 0)was assigned if there were "very high" number of holidays. To establish the limiting value for assigning a score of 0, the standard deviation (STD) was calculated for each evaluation parameter. The limiting value for the score of 0 was obtained based on having a three times the

STD of the evaluation parameter. The three times the STD limit was also used to eliminate the effects of outlier/extreme data for the ranking system. Values falling outside this limit were given a score of 0. Linear interpolation was used to determine scores between 10 and 0. For example when using the parameter of "holidays," the standard deviation was 2.4 holidays per sample and a score of 0 was assigned for coating samples that resulted in a 7.2 STD (3 x 2.4 = 7.2). This approach was used for all performance parameters except the percent change in gloss. Since gloss retention values were on the percent basis, the values of 0% and 100% were used accordingly.

Table 25 lists the 0 and 10 scores for each of the evaluation parameters for the coating systems used in this study. In addition, the score for each coating system based on individual or specific evaluation parameters is shown in Table 26. Table 27 lists the weighted average values for each coating system and the final ranking score. It should be noted that these rankings do not take into account the out-gassing craters that were present on the powder coated samples. Until this problem is corrected these coating systems would not be a viable option for recommended use. In addition, coating system SW-3F experienced white spots in varying locations on the samples. Since these white spots did not cover the entire coating surfaces, the correct changes in color is not necessarily reflected in the measured ΔE values due to the fact that multiple readings had to be taken at different locations on the samples. The white spots have a far greater effect on aesthetics than the ΔE value indicated.

Table 26: Upper and Lower Scores (0 and 10 scores)

	ΔE	% Change in Gloss	Rust Creepage	Mean Holidays
Poor Performance Value (0 Score)	7.123[1]	100	1.449[1]	7.193[1]
Exceptional Performance Value (10 Score)	0	0	0	0
Standard Deviation	2.374	26.463	0.483	2.398

[1]Value calculated using three times the standard deviation

Table 27: Ranking of Evaluation Parameters

	ΔE	ΔE Ranking	% Change in Gloss	Gloss Ranking	Rust Creep	Creepage Ranking	Mean Holidays	Holiday Ranking
CB-2	1.292	8.19	22.267	7.77	0.836	4.23	0.4	9.44
PPG-2	8.238	0	32.083	6.79	1.281	1.16	2.8	6.11
CB-D	1.375	8.07	57.377	4.26	0	10	1.6	7.78
SW-D	0.509	9.29	38.236	6.18	0	10	0.4	9.44
WA-D	0.953	8.66	94.513	0.55	0.558	6.15	8.0	0
CB-3P	1.459	7.95	61.271	3.87	0.881	3.92	0.2	9.72
SW-3P	0.706	9.01	34.980	6.50	0.105	9.28	0	10
PPG-3P	2.724	6.18	49.682	5.03	0.546	6.23	0	10
CB-3F	0.411	9.42	12.474	8.75	1.072	2.60	0	10
SW-3F	0.806	8.87	5.010	9.50	0	10	0	10
SW-05PD	0.285	9.60	0.940	9.91	0	10	1.6	7.78
SW-04PD	5.082	2.86	45.159	5.48	0	10	4	4.44

Table 28: Weighted Ave. Values and Final Rankings

	Weighted Ave. Score	Final Ranking
CB-2	7.68	6
PPG-2	2.79	12
CB-D	7.36	7
SW-D	8.64	3
WA-D	4.96	10
CB-3P	6.59	8
SW-3P	8.57	4
PPG-3P	6.47	9
CB-3F	8.32	5
SW-3F	9.37	2[2]
SW-05PD	9.46	1[1]
SW-04PD	4.83	11[1]

[1]Does not take into account initial out-gassing craters
[2]System had white spots that would affect aesthetics

Fluoropolymer powder coat system SW-05PD scored as the best performing coating system according to color retention, retention of gloss, minimum rust creepage, and minimum holidays. Again, the initial out-gassing craters are not considered here. However, this coating most likely will not have a satisfactory performance for bridge application due to the presence of these initial out-gassing craters. To be considered for use in bridge application, the manufacturer of this coating will need to be able to eliminate the formation of the out-gassing craters from this coating system. This initial out-gassing was also present on the polyester powder coat system SW-04PD. Coating system SW-04PD was assigned the second lowest overall score since it exhibited the second highest change in color.

Fluoropolymer 3-coat system SW-3F was scored as having the second best performance. The score for this coating system did not reflect the spotty color fading since the measured color change values were taken at limited number of locations on the surface of each coated sample. This can, however, have an adverse aesthetic effect on the appearance of this coating system Coating system CB-3F had the 5th overall ranking due to slightly higher rust creepage. Overall,

the fluoropolymer coating systems had the smallest change in color and gloss and were found to be among the top performing coating systems in this study. Considering the high cost of fluoropolymer coating systems and a somewhat comparable performance of other systems, these coating systems may not become the highest choice for application to bridge railing structures.

Among the liquid duplex coating systems, the coating system SW-D was scored as having the highest overall ranking (3rd, 8.64), followed by CB-D (7th, 7.36), and WA-D (10th, 4.96). These coating systems resulted in good visual appearance.

Three-coat polyurethane systems CB-3P and PPG-3P were assigned similar overall scores and were ranked as 8th (6.59) and 9th (6.47), respectively, among the coating systems used in this study. Coating system SW-3P performed the best of the 3-coat polyurethane systems and was 4th in overall ranking with a score of 8.57.

Among the three duplex and the 3-coat polyurethane systems, two systems (SW-D and SW-3P) were coated with the same top-coat material. It was found that in general duplex systems performed better than the 3-coat zinc-rich polyurethane coating systems.

Between the two 2-coat systems, system CB-2 performed well but system PPG-2 was assigned the lowest overall score and ranking. However, with having only two 2-coat coating systems in this study a conclusion on the effectiveness of 2-coat systems cannot be made with a high degree of confidence.

6.0 Summary/Conclusion, Recommendations, and Future Work

6.1 Summary/Conclusion

Laboratory accelerated weathering tests of coating systems are not substitutes for real outdoor environmental exposure but may be used to estimate how a coating system will perform over the years. By exposing coating systems to harsh environmental conditions in the laboratory and evaluating various performance parameters, accelerated weathering tests may be used to significantly decrease the time needed to evaluate the effectiveness of coating systems.

Coating selection, surface preparation, and application are equally important for acceptable performance of coating systems. At a minimum, it is important to follow manufacturers' recommendations and applicable specifications when coatings are used for aesthetic and to protect steel railings in bridges. In addition, special provisions and specifications from the bridge owners must be followed to enhance the effectiveness of a coating system.

In a number of bridge and railing structures, WisDOT engineers have experienced problems with the adhesion of coating systems in duplex coating systems. The primary problem has been the loss of adhesion at the interface of the coating material and the galvanized substrate. This has rendered such coating systems ineffective in terms of aesthetic. In this study, it was shown that by following proper galvanization procedures and surface preparation procedures, it is possible to achieve effective coating on galvanized steel with good adhesion characteristics. Test results showed that in most cases the duplex coating systems gained greater adhesion properties than zinc-rich 2- and 3-coat systems. The enhancement was observed both after the initial coating application and after the completion of the accelerated weathering tests. The surface preparation was made using Garnet abrasive material for brush-

off blasting (SSPC-16) with a lower air pressure (40 to 45 psi), resulting in a matte finish with a mean surface profile of 1.2 mils.

The two 2-coat coating systems tested in this study did not produce similar results. One system performed well which was similar to that of the three-coat polyurethane systems used in the study and the other 2-coat system showed very poor performance. Without testing additional 2-coat coating systems, it will be difficult to draw a general conclusion on the overall performance of all 2-coat coating systems. For 2-coat systems to be effective, correct application by skilled operators is essential. Unlike 3-coat systems, 2-coat systems have smaller tolerance to deficient application. In a 3-coat system, there is one additional coat, or layer of protection, that overcomes deficient coating application that may have been placed in some areas. The effectiveness of the 3-coat systems can be seen especially in aesthetic railings where usually there are complex geometries. These complex geometries contain structural details and areas that are hard to reach during coating application and this may result in smaller coating thickness. If 2-coat systems are to be specified and used for steel railing components, extra care must be taken to ensure proper coverage in all areas.

From the results of the study, it was found that the best aesthetic performance in terms of color and gloss retention was achieved by the fluoropolymer top coats followed by polyurethane top coats. The best performance in terms of durability was achieved by the duplex systems used in the study. Ideally, it would be expected that the best overall performance for both aesthetics and durability would be achieved by a duplex system with a fluoropolymer top coat. However, the study included only polyurethane top coat in the duplex systems. No fluoropolymer top coat was used in the duplex systems.

When comparing conventional 3-coat systems with duplex systems supplied by the same manufacturer, superior performance was observed for the duplex systems. The observed

better performance is primarily due to the benefits of minimizing corrosion from the superior protection offered by the galvanized steel. While achieving better performance, the initial cost of a duplex system is generally the same as that for 3-coat systems and generally the maintenance cost during the service life of the structure will be lower.

For aesthetic railings, duplex systems offer several benefits. Even in areas where the coating system is damaged or has localized failure (i.e. sharp edges and splice locations), the galvanization remains intact and prevents rust bleeding of the substrate. Several bridges with non-galvanized railing that were inspected for this study have experienced significant rust bleeding at splice locations. The rust bleeding resulted in stained concrete parapets and walls and projecting unpleasant appearances that have negatively impacted the aesthetics of these bridges.

In liquid coating systems, surface tension forces developed during the drying time can generally reduce the dried film thickness (DFT) along sharp edges of structural components. Galvanization can offer additional protection along sharp edges and corners where lower DFT is generally resulted. In aesthetic railings, there are usually multiple pieces that are welded together that result in complex geometries. This makes it difficult for adequate coating materials to be applied at such difficult areas. Accordingly, these areas are more susceptible to localized corrosion failure (i.e. welds and interior and exterior corners). Additional problems that are observed at interior corners include trapped moisture and lack of adequate coating materials due to tension forces developed during the drying process. Galvanization of railings reduces such problems and can help give proper protection to these areas.

The galvanization process for bridge railings offers additional benefits during the service life of such railings. Holes drilled in railings to prevent entrapped air during the galvanization process, help drain water from the railings during the service life. This helps to prevent the

accumulation of water and excessive expansion during cold temperatures that can cause major damage to railings. Also, the galvanized inside surfaces of the railings can offer a better corrosion protection.

It has been noted in the Special Provision for galvanized railings, that railings must be blasted per SSPC-SP6 to remove mill scale prior to galvanization. A review of the available literature and recommendations by the galvanizing industry suggest that this process may not be necessary. The rationale is that during the galvanization process steel is immersed in an acid bath (pickling) that is expected to remove most of the mill scale and surface corrosion from the steel.

The duplex powder coating systems used in the test program for this study showed significant problems during the application stage. Two different powder coat systems were included in this study, a mid-grade (polyester) and a top-grade (fluoropolymer) system. It was found that the fluoropolymer powder coat system performed very well for color and gloss retention. The polyester powder coat system, however, did not perform well for color and gloss retention. The most significant problem with the selected powder coating systems in the study was determined to be the coating application. Since powder coating application requires special skills and facilities, the process was performed by skilled specialists associated with the respective manufacturer. During the application of both powder coat systems, it was found that extensive out-gassing problems existed that created multiple small craters or bubbles in the finished powder coat surfaces. The manufacturer made several unsuccessful attempts to eliminate these craters by introducing various additional amounts of a paraffin-based anti out-gassing agents. Although the number of craters were reduced significantly for the final coating material and application, they were not fully eliminated. During the testing program, these out-gassing craters were turned into holidays that compromised the full protection against corrosion

of the substrate. These coating systems were determined not to be a viable option for use on aesthetic bridge railings due to potential high cost and until the out-gassing problem is resolved by the manufacturer.

Similar to galvanization, the size of members for powder coating is limited to the size of the curing oven and coating of large section sizes may not be cost effective or practical. Powder coat systems require higher cost than conventional 3-coat liquid or duplex coating systems.

6.2 Recommendations

Recommended language revisions for the 2013 WisDOT Standard Specifications and Special Provision are provided in Appendix D of this report. Additional and more specific recommendations for use of coating systems in bridge railings are provided below:

I. For all aesthetic bridge railings, it is recommended that only galvanized liquid duplex coating systems be used in the future. Coating systems CB-D and SW-D from this study performed well and are recommended to be accepted as approved coatings systems and for future use for bridge railings. Although more expensive, duplex systems with fluoropolymer top coats seem to yield the best overall performance in terms of both aesthetics and durability. Such systems were not, however, included in the test program for this study but should be included in a future study to verify the expected performance.

II. For galvanized railing members, special attention must be paid to surface preparation (see Appendix D for details) and fabrication of adequate number of vent holes in required locations. These vent holes can also be effective in minimizing any water entrapment inside railings that could potentially cause severe damage, i.e., cracking, due to freezing and expansion.

III. If non-galvanized steel is used for bridge railings, adequate drainage of water must be provided through fabricating adequate number of drilled holes and offering proper slopes to

prevent water from becoming trapped inside the railings. Use of small holes should be avoided as they become clogged easily with debris. In addition, use of expansion joints and splice connections must be avoided or they must be properly designed to eliminate points of water entry, and excessive physical damage to the coating materials due to surface friction.

IV. For large plate girders and other sections where galvanization process is not practical, it is recommended to use conventional 3-coat polyurethane coating systems. Use of 2-coat systems is not recommended since only two systems were included in the test program of this study that yielded inconclusive results. Additional 2-coat systems should be included in a future test program to establish their viability for use in steel bridge railings. It is recommended that more attention and verification be placed on stripe coating of plate edges and areas prone to coating failure (as required per Standard Specification 517.3.1.7.2).

V. Fluoropolymer coating systems provided the best color and gloss retention in this study but they did not necessarily provide a better corrosion resistance when compared with conventional 3-coat polyurethane coating systems. Fluoropolymer top coats used in duplex systems seem to offer the best aesthetics and durability performance but they require additional cost.

6.3 Future Work

Future studies that could be beneficial to the WisDOT in terms of using effective coating systems for bridge steel railings will include expanding the number of coating systems and colors that have been subjected to laboratory testing under this study including fluoropolymer top coats in duplex systems, and performing outdoor exposure tests for the selected coating systems.

6.3.1 Testing Additional Coating Systems

Recommended additional testing of coating systems includes:

I. Investigate the performance of additional coating systems to arrive at a better understanding of the comparative performance of a greater number of coating systems that can be included in

the WisDOT's list of approved products. For example, for the 2-coat systems only two systems were included in the testing program during this study. One of these coating systems performed well and the other did not. Accordingly, it is not possible to draw a conclusion on the overall performance of 2-coat systems.

II. From the results of this study, it was found that the best aesthetic performance was achieved by fluoropolymer top coats while the best durability performance was achieved by duplex systems. Accordingly, it seems that the best overall performance in terms of both aesthetics and durability would be achieved by duplex systems that have fluoropolymer top coat. A new study of the performance of such systems should be conducted to verify the expected high performance.

III. Additional special tests for coating systems with different colors are recommended. Only limited tests will be necessary for the coating systems that have already been included in the full testing program for this study. The required tests for this group of coating systems will be only those using the Xenon Arc testing that exposes the coatings to the full spectrum of sunlight and particularly to the longer wave-length UV radiations. It has been shown by this and other studies that different colors can perform differently, i.e., in terms of color and gloss retention and fading, when they are subjected to longer wave-length UV radiations.

III. Evaluating the performance of edge retentive epoxy mid-coating materials on geometries with sharp edges and discontinuities to determine their performance effectiveness. It is known that sharp edges in coated structures generally will have a reduced dried film thickness (DFT) due to surface tension forces of the coating materials during the drying process. This results in some areas of the structure that are more susceptible to premature coating failures. Also, studying the effects of stripe coating on edges can determine the effectiveness of using appropriate edge retentive coating materials for protection against corrosion.

6.3.2 Outdoor Testing

While laboratory tests can provide good understanding of the performance of various coating materials in a short time relevant to the service life of the coated structures, it cannot fully replace a true exposure to outside environment over a longer period of time. The following is recommended to address this:

I. Perform accelerated outdoor testing on all of the coating systems that were included in the testing program for this study. During these tests, while the coated samples are exposed to outside environment they will be subjected to cycles of wet-dry sodium chloride solution to accelerate the corrosion process. Exposure to the outdoor environment will introduce the effects of additional site-specific factors, including true temperature variations, humidity, intrusive chemicals/particles in the air, UV, and others on structural elements that are coated with various coating systems. These factors cannot generally be included in the laboratory accelerated testing. The accelerated outdoor tests can be used to complement the results of the laboratory accelerated weathering tests.

II. In order to include the longer term and site-specific effects on the performance of coated steel railings, railing sections coated with the systems that were included in this study will be placed at the sites of a selected number of Wisconsin bridges throughout the state. The advantage of these tests will be including the effects of additional parameters such as wind, sun, and proximity of water as well as other effects such as being within the splash zone of the traffic for water, salt, gravel and other debris.

III. Various new coating systems, either from the recommended coatings in this study or other coatings that are routinely applied to new or existing structures in Wisconsin, should be included in a multi-year monitoring program to evaluate their performance and effectiveness

under real field conditions. The results of such monitoring can offer an effective verification of the laboratory accelerated weathering testing. If the accelerated laboratory tests are verified, future accelerated tests can be performed to evaluate the performance of new or other coating materials in reasonable time spans and with relatively low cost.

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Appendix A: Survey Results

Regional DOT Questionnaire and Summary Responses

Regional DOT	Response
Madison/South West Region	Yes/Provided Structural Details
Lacrosse/Southwest Region	Yes/Filled out questionnaire
Milwaukee/Southeast Region	No
Green Bay/Northeast Region	Yes/No records Kept
Wisconsin Rapids/North Central Region	No
Rhinelander/North Central Region	No
Eau Claire/Northwest Region	No
Superior/Northwest Region	No

Questionnaire/Responses (WisDOT Districts)

1. Is there a list of steel railing and concrete coatings that have been used in the past several years in your District? If yes, please provide or attach list(s) with coating type and manufacturer.

    A. What type of coatings have performed well, and what type of coatings have performed poorly?
        - SOME Two part epoxy paint for steel has performed poorly. One very large bridge painting project in particular had failures that occurred in the first year. (Other small bridges with similar or same product had no problems.)
        - Some concrete stains have faded.

    B. What are the unit costs associated with these coatings?
        - None Given

    C. Please list/specify any new coatings being used in your district?
        - In the last five years we have been placing epoxy overlays on some our bridge decks that are in good condition. There seems to be an expanding list of contractors and manufacturers of the epoxy product and the aggregates that are recommended.

    D. Has your District used any graffiti resisting coatings? If so, please specify such coating(s) and their performance.

- Yes, we have used graffiti resistant coatings.
- Type = Sherwin Williams – Invisi-Shield Anti-graffiti – Clear. (B-32-0202)

E. Has your district used anodized aluminum railing? If so, please specify railings and their performance.
    - None

2. What type of coating failures has your District experienced in the past?
    - As I stated above, the Two-part epoxy paint (mfg = Sherwin Williams) is by far our most costly coating/paint failure.
    - We do have a few paint failures of decorative steel railing which was galvanized under the paint. No rust is expected, but aesthetics are an issue.

A. Is there a list of bridges with concrete or steel railing coating failures? If yes, please provide or attach list of bridges and type of failures.
    - B-32-0198 – steel railing paint over galvanized steel
    - Some of these – not sure which ones: B-62-0204, 0118, 0119, 0187, 0120, 0121, 0122, 0123, 0188, 0202 (all in the Kickapoo reserve on STH 131)
    - Retaining wall: R-32-0033

B. What is the main type of coating failure for steel railings, and for concrete bridges?

    - What are the specific coatings associated with these failures, i.e. manufacturer and system?
        - None Stated

C. Are there specific structural details or areas of bridges and railings that experience more coating failures? If yes, please specify.
    - Salt Spray zones on steel; In fact, if you look at the bridge in the direction the snow plow travels, you see complete failure. If you look against the direction that the snow plow travels, you can barely notice the failure.

D. What type of steel railing has the most coating failures or rust bleeding?
    - Decorative railing

    - What are the coatings associated with these railings?
    - Paint over galvanized steel.

3. Are there plans, shop drawings, specifications, special provisions, and installation guidelines for structural details of concerns (steel railings…) that can be provided to the research staff?
    - Yes.

4. Please list any additional information or comments that may aid to this study.

5. May we have the contact information for the person who is filling out this questionnaire? The results of this study will be forwarded to you.

Manufacturers Questionnaire and Summary Responses

Manufacturers	Response
Sherwin Williams	Yes
Tnemec	Yes
Carboline	Yes
AkzoNobel/International	No
PPG/Ameron	No
TK Products	No
MAB	No
Tex-Cote	Yes/Provided Product Information

Questionnaire/Responses (Manufacturers)

1. Does your company have specific coatings designed to be painted over galvanized surfaces? If yes, please list these coatings.
    - Tnemec
        - Series 115, 66, 161 and more. Most Tnemec coatings can go over galvanized steel with proper surface preparation
    - Sherwin Williams
        - Zinc Clad 5 Organic Zinc-Rich Primer is used to touch-up damaged and/or rusted areas of galvanized steel.
        - Macropoxy 646 Fast Cure Epoxy is applied to galvanized steel.
        - Acrolon 218 HS Acrylic Polyurethane is used as a topcoat over Macropoxy 646 to provide color and gloss retention
        -

B. Please provide the application and surface preparation procedures with these coatings.
    - SSPC SP7, spray, roller or brush application
    - SSPC-SP16 is the industry standard for preparation of galvanized steel

2. Does your company have specific coatings for non-galvanized steel railings? If so please list the coatings.
    - Tnemec
        - Series 1, 66, 161, 90-97, 27, 135
    - Sherwin William
        - Zinc Clad III primer, Macropoxy 646 intermediate coat, Acrolon 218 HS top-coat
        - Corothane I Galva-Pac Zinc primer, Polysiloxane XLE top-coat
    - Carboline

        - Carbozinc 11 HS / Carboguard 888 / Carbothane 133 LH
        - Carbozinc 859/ Carboguard 888 / Carbothane 133 LH

    B. What are the differences and specific benefits of these coatings?
        - Tnemec
            - 90-97 is zinc rich coating and provides cathodic protection (better than galvanizing)
        - Sherwin Williams
            - The advantage of the two 2-coat systems is that they save the labor involved with applying one coat, they reduce the time required to complete the project, and when properly applied there is no sacrifice in quality.

    C. Please list any specific coatings used for maintenance.
        - Tnemec
            - series 27, 135, 1
        - Sherwin William
            - Zinc Clad 5 for spot repairs
        - Carboline
            - Carbozinc 11 HS / Carboguard 888 / Carbothane 133 LH
            - Carbozinc 859/ Carboguard 888 / Carbothane 133 LH

3. Does your company have specific coating designed to be applied over anodized aluminum? If yes, please list these coatings.
        - Sherwin Williams
            - Acrolon 218 HS Acrylic Polyurethane is used as a top-coat over Macropoxy 646 tie-coat

    B. Please provide the application and surface preparation procedures with these coatings.
        - Tnemec
            - SSPC SP2, SP3. SP7 depends gauge aluminum
        - Sherwin Williams
            - SSPC-SP 16
        - Carboline
            - Refer to product Data Sheet

4. Does your company have specific coatings designed for concrete application? If yes, please list these coatings.
        - Tnemec

        - Cementitious block filler 130, Tnemec acrylic polymer 156, Series 180. If interior concrete we have epoxies, pigmented silane/siloxane water repellant coatings- Chemprobe 600 series
    - Sherwin William
        - SWD Bridge and Highway Stain
        - Loxon Vertical Concrete Stain
        - UltraCrete Solvent Borne and Textured Masonry
        - DOT Concrete Texture Coating
    - Carboline
        - Carboguard 510
        - Semstone 800
        - Semstone 884
        - Semstone 300/305

B. Please specify any coatings designed to replicate natural stone coloring.
    - Sherwin William
        - H & C Decorative/ Concrete Stain

C. Please specify any coatings that specifically offer resistance to chloride ion penetration into concrete substrate.
    - Tnemec
        - Chemporbe 600 series
    - Sherwin Williams
        - DOT Concrete Sealer 100
        - Silane (SW244-40)
        - Siloxane (SW 233 and HB-150)

D. Please specify any coatings or penetrating stains that can be used to add aesthetic coloring to concrete.
    - Tnemec
        - Series 607 is pigmented for vertical concrete substrate
    - Sherwin Williams
        - H & C Decorative/ Concrete Stain

E. Please specify any coatings used for maintenance.
    - Tnemec
        - Series 180, 156, 600
    - Sherwin William
        - Maintenance Preformed Using Original Coatings

F. Please list surface preparation and application procedures that are used for the previously listed concrete coatings.
    - Tnemec
        - 600 – clean & dry
        - Acrylic polymers – SSPC SP13
    - Sherwin Williams
        - SSPC-SP13, Clean and Dry, Cure for 28 Day, High Pressure Water Cleaning at Minimum 3000psi

5. Does your company have any specific steel or concrete coatings to protect against graffiti resistance? If so, please list these coating(s).
    - Tnemec
        - 626 & V626 (Non sacrificial)
        - 370 graffiti cleaner
    - Sherwin Williams
        - 2K Urethane Anti-Graffiti
        - Invisi-Shield
        - Anti-Graffiti Coating B97

6. Does your company have specific coating application procedures for various structural details? (i.e., corners, sharp edges, bolt holes, drain, vent holes, field erection, expansion joints etc.). If so, please specify.
    - Tnemec
        - 135, 69, - Sharp Edges
    - Sherwin Williams
        - AASHTO/NSBA Guide Doc S-8.1
    - Carboline
        - NACE RP0178-2003

B. Please list any specific coatings that are designed for these structural details.
    - Sherwin Williams
        - Zinc-Clad DOT Inorganic Zinc-rich Primer
        - Zinc-Clad III HS Organic Zinc-rich Primer
        - Corothane I Galva-Pac Zinc Primer

7. Please list any additional information or comments that may aid to this study.
    - More questions need to be asked because these questions skim the surface of what we have available
    - Surface Preparation, Product Selection, and Skilled Application, Needed for Successful Coating

8. May we have the contact information for the person who is filling out this questionnaire? The results of this study will be forwarded to you.

State DOT Questionnaire and Summary Responses

States	Response
Alabama	Yes/Provided Specifications
Alaska	Yes
California	no
Connecticut	no
Florida	no
Idaho	no
Indiana	no
Iowa	no
Louisiana	no
Maine	no
Michigan	no
Minnesota	no
Nebraska	no
New Hampshire	Yes/Provided Specifications
North Carolina	no
Ohio	no
Oregon	no
Pennsylvania	no
South Dakota	Yes
Vermont	no
Utah	Yes
Virginia	Yes
Washington	no
West Virginia	no

Questionnaire/Responses (State Highway Agencies)

Wisconsin Highway Research Program

"Aesthetic Coatings for Bridge Components"

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1. Does your state maintain an approved product list for steel railing and concrete coatings? If so, please attach list(s), or indicate website link.

   Concrete coatings approved product list (please state yes or no); Yes, Virginia, South Dakota

   Steel railing coatings approved product list (please state yes or no); Yes, Utah, South Dakota

2. Please list all steel railing coatings that your state has used in the last 10 years for bridge and highway components, along with the following information:
   a. Type of coating (new or maintenance)
   b. The extent to which the coating has been used (limited, moderate, or extensive)
   c. The application of the coating (i.e. coating over bare steel, coating over galvanized steel, etc.)
   d. The intended use of the coating (i.e. aesthetics, rust inhibitor, chloride protection, graffiti resistance, etc.)
   e. Installation guide (i.e. application processes in which the coating is applied)

Steel Railing Coating Product Name & Manufacturer	**New or Maintenance**	**Extent of Use (limited, moderate, extensive)**	**Application**	**Intended Use**	**Installation Guide**
Zinc Rich Primer With Polyurethane Top-Coat	New	Extensive	Bare Steel	Aesthetics, Rust Inhibitor	Spray On
Galvanized	Moderate	Limited	Bare Steel	Rust Inhibitor	Hot-Dipped
NEPCOAT Qualified Products List A	New	Limited	New and 100% bare existing	aesthetics, rust inhibitor, chemical/environment	3-coat system See website for details

NEPOVERCOAT Qualified Products List M	Maintenance	Limited	Previous painted Existing	aesthetics, rust inhibitor, chemical/environment	2 or 3-coat system See website for details

3. Please list any coating problems associated with the previously listed steel railing coatings (i.e. durability, peeling, fading, rust bleeding, adhesion, vandalism, etc.), and any remedial actions taken, if any.

	Coating Problems			
Steel Railing Coating	**Application Problems**	**Performance Problems**	**Cause of the Problem**	**Action Taken**
Paint	Field Splices are Problem Areas Due to Field Application of Paint	Minor Fading, Rust Bleeding	Nicks, Scratches, Splices	none
Galvanized	Field Splices, Due to Field Application of Touch-Up	Normal Fading	Oxidation of Field Touch-Up	none
Existing Zinc Coatings	-	durability, peeling, fading, rust bleeding, adhesion	-	-
Existing Aluminum Coatings	-	rust, vandalism	-	Remove and replace with new railing (rust) Replace missing section (vandalism)

4. Please list any coating successes, type of success, and reason for the success for the previously listed steel railing coatings.

Steel Railing Coating	**Type of Success**	**Reason for Success**
Galvanization	No Rust Bleeding at Nicks or Scratches	Galvanization

5. Please provide an average current cost for each steel railing coating listed above. Please provide material costs, labor costs, maintenance cost per year, and a brief description of what these costs include.

Steel Railing Coating	Material Cost (per linear foot)	Labor Cost (per linear foot)	Maintenance Cost (per linear foot)	Costs Description
Zinc/epoxy or urethane/polyurethane	-	-	-	Most expansive 6 ft. new decorative railing: $500/ft, New coat: $20/sq. ft. Overcoat: $6/sq. ft.

6. Does your state maintain any standard structural details and specifications for coating applications on steel railings, etc? (Please state yes or no); Yes Utah If yes, please attach list or indicate website link.

7. Has your state used anodized aluminum railings in the past? If so, please list the manufacturer(s) and performance of the railings. Additionally, please list any coatings, application procedure, and manufacturers that have been used for these railings.

Aluminum railing systems were used on a portion of the bridges previously constructed by Virginia. These railing systems consisted of cast aluminum posts and aluminum extruded tube rails (ASTM B221, alloy 6061 – T6 or 6351 – T5). No coatings were applied to these aluminum railing system components, and there have been no significant issues with the performance of these railing systems.

8. Has your state used galvanized painted railings in the past? If so, please list coating type, application process, and manufacturer.

Virginia constructed a limited number of bridges using galvanized, painted steel components in the past.

Steel railing systems are used on a portion of the new bridges currently being constructed in Virginia. The material in these railing systems consists of ASTM A500 Grade B steel, and all components are hot dip galvanized, with no other coating applied.

Alaska used MC Zinc primer, MC mionatic intermediate, and MC Shieldcoat top-coat by Wasser High Tech

9. Has your state noticed any warping of railings after being galvanized? If so, please list type of railings and if there been anything done to correct this issue.

There have been no significant issues with warping of galvanized railing components, but some with other items.

10. Has your state noticed any colors that have been more susceptible to fading for steel railings? If so, please list the coating(s), color(s), and manufacturer(s).

None

11. Please list all concrete coatings and stains that your state has used in the last 10 years for bridge and highway components, along with the following information:

a. Type of coating (new or maintenance)
b. The extent to which the coating has been used (limited, moderate, or extensive)
c. The application of the coating (i.e. parapets, girders, piers, abutments, wing walls, sound barriers, etc.)
d. The intended use of the coating (i.e. aesthetics, concrete coloring, rust inhibitor, chloride protection, graffiti resistance, etc.)
e. Installation Guide (i.e. application processes in which the coating is applied)

Concrete Coating Product Name & Manufacturer	**New or Maintenance**	**Extent of Use (limited, moderate, extensive)**	**Application**	**Intended Use**	**Installation Guide**
Tex-Cote - Textured Coatings of America	Maintenance	Extensive	Parapets/Railing Systems	Aesthetics, Crack Sealing, and Chloride Protection	Surface preparation and application performed in accordance with the manufacturer's recommendations – technical data sheet attached to email returning this survey
Tamms Coat – Tamms	Maintenance	Moderate	Parapets/Railing Systems	Aesthetics, Crack Sealing,	Surface preparation and application performed in accordance with the

				and Chloride Protection	manufacturer's recommendations – technical data sheet attached to email returning this survey
Thorocoat – BASF Construction Chemicals	Maintenance	Moderate	Parapets/Railing Systems	Aesthetics, Crack Sealing, and Chloride Protection	Surface preparation and application performed in accordance with the manufacturer's recommendations – technical data sheet attached to email returning this survey
Silicone acrylic concrete sealer	New	Moderate	parapets, girders, piers, abutments, wing walls, retaining walls	aesthetics, concrete coloring, some chloride protection	Dry surface, Minimum of two coats, Re-clean through cure before the second coat, apply tinted concrete sealer
Silicone acrylic concrete sealer	Maintenance	Limited	parapets	aesthetics, concrete coloring, some chloride protection	Dry surface, Minimum of two coats, re-clean through cure before the second coat, apply tinted concrete sealer to match existing
Commercial Texture Finish	Both	Moderate	Parapets, Girders, Piers, Abutments, Wing-Walls, Retaining Walls	Aesthetics and Reflectivity	Spray or roll applied
Stain (Custom Rock)	New	Limited	Retaining and Wing-Walls	Aesthetics	Spray and Sponge Applied

12. Please list any coating problems associated with the previously listed concrete coatings or stain (i.e. durability, peeling, fading, blistering, adhesion, vandalism, etc.), and any remedial actions taken, if any.

	Coating Problems			
Concrete Coating	**Application Problems**	**Performance Problems**	**Cause of the Problem**	**Action Taken**
Tex-Cote - Textured Coatings of America	No significant application problems	No significant performance problems		
Tamms Coat – Tamms	No significant application problems	No significant performance problems		
Thorocoat – BASF Construction Chemicals	No significant application problems	No significant performance problems		
Silicone acrylic concrete sealer	-	peeling, fading, blistering	Cracking, splash zone chemical/environ. exposure	reapply once through service life
Commercial / Texture	Need 28 day Cure on New Concrete	Fading and Adhesion	-	-

13. Please list any coating successes, type of success, and reason for the success for the previously listed concrete coatings.

Concrete Coating	**Type of Success**	**Reason for Success**
Tex-Cote - Textured Coatings of America	Coating provides improved appearance and protection from exposure conditions	Standard specification, approved products list, proper surface preparation and application
Tamms Coat – Tamms	Coating provides improved appearance and protection from exposure conditions	Standard specification, approved products list, proper surface preparation and application
Thorocoat – BASF Construction Chemicals	Coating provides improved appearance and protection from exposure conditions	Standard specification, approved products list, proper surface preparation and application
Silicone acrylic concrete sealer	Minor fading, blistering of parapets	

Commercial Texture	Most application have been successful and durable	Good product and application
Stain (Custom Rock)	No Problems to date	Sealed with expensive sealer

14. Please provide an average current cost for each concrete coating or stain listed above. Please provide material costs, labor costs, maintenance cost per year, and a brief description of what these costs include.

Concrete Coating	**Material Cost (per square foot)**	**Labor Cost (per square foot)**	**Maintenance Cost (per square foot)**	**Costs Description**
Tex-Cote - Textured Coatings of America				Average installed cost by contract - $45 per LF of bridge – this cost includes all materials, labor, tools, and equipment necessary to complete the work – the Virginia contract item for Concrete Surface Color Coating is bid on a lump sum cost per bridge and the cost records do not provide a break down between material costs and labor costs
Tamms Coat – Tamms				Average installed cost by contract - $45 per LF of bridge – this cost includes all materials, labor, tools, and equipment necessary to complete the work – the Virginia contract item for Concrete Surface Color Coating is bid on a lump sum cost per bridge and the cost records do not provide a break down between material costs and labor costs
Thorocoat – BASF Construction Chemicals				Average installed cost by contract - $45 per LF of bridge – this cost includes all materials, labor, tools, and equipment necessary to complete the work – the Virginia contract item for Concrete Surface Color Coating is bid on a lump sum cost per bridge and the cost records do not provide a

				break down between material costs and labor costs
Silicone acrylic concrete sealer	-$0.5	-$0.5	-	Average $1.0/sq. ft. labor and material construction cost
Commercial Texture Finish				$3.15 per square foot total cost on existing concrete

15. Does your state/office maintain any standard structural details and specifications for coatings applications on concrete components, parapets, piers, abutments, wing walls, sound barriers etc?
(Please state yes or no);_____Yes Utah, Virginia_____ If yes, please attach list or indicate website link.

16. Has your state noticed any colors for concrete coatings that are more susceptible to fading? If so, please list coating(s), color(s), and manufacturer(s)

Virginia typically specifies the color of the Concrete Surface Color Coating to be Grey – there have been no significant issues with fading of this color

17. Does your state maintain any evaluation program for steel railing or concrete coatings? If so, please specify below or provide a web link if available.

The Concrete Surface Color Coating products listed on the Virginia Approved Products List are evaluated by the Virginia DOT Materials Division using standard product evaluation methods. A link to the Virginia DOT Materials Division new product information web site follows: http://www.virginiadot.org/business/bu-materials-New-Products.asp

18. Does your state/office maintain any in-house testing procedure(s) for steel railing or concrete coatings? If yes, please describe your program with contact information for the person in charge or provide a web link if available. No

19. Please list any additional information or general comments on coatings that may aid to the success of this study.

As mentioned in the response to Question 1, Virginia does not currently maintain an approved list of coatings for steel bridge railings – the occasional use of coatings on steel railings is performed in accordance with the standard specification for bridge painting – Section 411 of the standard specifications – a copy of this specification is attached to the email returning this survey.

Virginia maintains a Special Provision for Concrete Surface Color Coating and an Approved Products List for Hydraulic Cement Concrete Sealants, Stains, and Coatings – copies of these documents are attached to the email returning this survey. The Special Provision for Concrete Surface Color Coating serves as the specification for coating concrete bridge railing systems and parapets. The coating of concrete bridge railing systems and parapets is typically preformed by contractors, and the contract bid item is lump sum per structure. The Special Provision requires that Concrete Surface Color Coating products be selected from the Department's current list of approved concrete surface color coatings, and that the material be applied in accordance with the manufacturer's recommendations.

South Dakota- Has switched from painted steel railings to galvanized steel railings due to rusting on painted rails.

20. May we have the contact information for the person who is filling out this questionnaire? The results of this study will be forwarded to you.

Appendix B: DFT and Color/Gloss Values

DFT Values

CB-2

Sample #	AVE DFT Zinc	AVE DFT Top	AVE Total DFT
1	5.6	4.4	9.9
2	4.3	3.9	8.1
3[1]	4.8	4.2	9.0
4[1]	4.8	3.8	8.6
5	4.6	3.9	8.5

[1]Scribed Samples

PPG-2

Sample #	AVE DFT Zinc	AVE DFT Top	AVE Total DFT
1	4.2	3.3	7.4
2	5.0	3.4	8.4
3[1]	4.7	3.5	8.2
4[1]	5.0	3.7	8.7
5	5.2	3.9	9.1

[1]Scribed Samples

SW-D

Sample #	AVE Galvanization DFT	AVE Tie DFT	AVE Top DFT	AVE Total DFT
1	5.9	2.0	3.0	11.0
2	5.9	3.1	2.4	11.4
3	5.7	3.3	2.2	11.1
4[1]	4.8	3.0	2.4	10.2
5[1]	5.6	3.1	2.8	11.5

[1]Scribed Samples

WA-D

Sample #	AVE Galvanization DFT	AVE Tie DFT	AVE Top DFT	AVE Total DFT
1	5.1	3.2	2.5	10.7
2[1]	4.8	3.1	2.6	10.4
3[1]	5.0	3.1	2.9	11.0
4	4.9	3.0	2.1	10.0
5	5.8	2.9	2.0	10.7

[1]Scribed Samples

CB-D

Sample #	AVE Galvanization DFT	AVE Tie DFT	AVE Top DFT	AVE Total DFT
1	5.7	0.5	3.2	9.4
2	5.1	0.7	5.2	11.0
3	5.2	0.9	4.7	10.8
4[1]	5.3	0.8	3.7	9.8
5[1]	4.8	0.8	4.2	9.9

[1]Scribed Samples

CB-3P

Sample #	AVE Zinc Primer DFT	AVE Mid DFT	AVE Top DFT	AVE Total DFT
1[1]	4.0	3.0	3.2	10.2
2	3.3	3.3	3.2	9.8
3[1]	3.8	3.2	3.4	10.4
4	3.5	3.2	3.0	9.6
5	3.1	3.4	3.4	9.8

[1]Scribed Samples

CB-3F

Sample #	AVE Zinc Primer DFT	AVE Mid DFT	AVE Top DFT	AVE Total DFT
1[1]	3.4	3.1	2.5	9.0
2	3.5	3.4	2.5	9.3
3	3.8	3.2	2.5	9.5
4	4.7	3.9	2.4	11.0
5[1]	4.4	3.4	2.1	9.9

[1]Scribed Samples

SW-3F

Sample #	AVE Zinc Primer DFT	AVE Mid DFT	AVE Top DFT	AVE Total DFT
1	4.1	3.4	2.6	10.2
2[1]	4.2	3.0	2.2	9.5
3[1]	4.1	3.0	2.4	9.4
4	4.2	3.2	2.5	9.9
5	4.3	3.2	2.2	9.7

[1]Scribed Samples

SW-3P

Sample #	AVE Zinc Primer DFT	AVE Mid DFT	AVE Top DFT	AVE Total DFT
1	4.3	4.1	3.6	12.1
2[1]	4.2	4.0	3.1	11.3
3[1]	5.0	4.9	3.8	13.7
4	5.0	4.0	3.3	12.3
5	5.0	3.9	3.2	12.1

[1]Scribed Samples

PPG-3P

Sample #	AVE Zinc Primer DFT	AVE Mid DFT	AVE Top DFT	AVE Total DFT
1	4.1	4.5	4.7	13.3
2[1]	4.2	4.8	3.7	12.8
3	4.8	4.5	4.0	13.3
4[1]	4.6	4.7	4.0	13.3
5	4.9	4.7	4.2	13.8

[1]Scribed Samples

SW-05PD

Sample #	AVE Galvanization DFT	AVE Tie DFT	AVE Top DFT	AVE Total DFT
1	5.2	3.6	2.4	11.2
2	5.0	3.0	2.5	10.5
3[1]	5.4	3.1	2.8	11.3
4	4.8	3.5	2.8	11.1
5[1]	5.4	3.0	2.6	11.0

[1]Scribed Samples

SW-04PD

Sample #	AVE Galvanization DFT	AVE Tie DFT	AVE Top DFT	AVE Total DFT
1[1]	5.3	3.0	2.7	11.0
2	4.8	3.9	2.4	11.0
3[1]	7.1	3.0	2.7	12.8
4	4.8	4.0	2.4	11.2
5	5.1	4.1	2.2	11.4

[1]Scribed Samples

Freeze/UV/Prohesion

CB-2

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change in Gloss
Initial	25.195	-0.137	-0.254					70.1	
1	25.406	-0.183	-0.216	0.211	-0.046	0.038	0.222	64.7	7.6
2	25.537	-0.164	-0.290	0.342	-0.027	-0.036	0.346	64.4	8.1
3	26.019	-0.181	-0.494	0.824	-0.044	-0.240	0.860	63.6	9.3
4	26.054	-0.056	-0.706	0.859	0.081	-0.452	0.975	60.3	14.0
5	25.725	-0.024	-0.708	0.530	0.112	-0.454	0.708	59.3	15.4
6	25.933	-0.026	-0.698	0.738	0.111	-0.444	0.869	59.5	15.1
7	25.787	-0.043	-0.597	0.592	0.094	-0.343	0.692	58.4	16.8
8	26.008	-0.066	-0.702	0.813	0.071	-0.448	0.931	58.8	16.1
9	26.123	-0.087	-0.724	0.928	0.050	-0.471	1.043	57.9	17.4
10	26.483	-0.079	-0.842	1.288	0.057	-0.588	1.417	57.4	18.1
11	26.219	-0.068	-0.740	1.024	0.069	-0.486	1.136	56.2	19.8
12	26.174	-0.088	-0.733	0.979	0.049	-0.479	1.092	56.7	19.1
13	26.320	-0.108	-0.750	1.125	0.029	-0.496	1.230	56.8	19.0
14	26.263	-0.080	-0.686	1.068	0.057	-0.432	1.155	55.0	21.6
15	26.371	-0.072	-0.780	1.176	0.065	-0.526	1.292	54.5	22.3

PPG-2

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
Initial	25.484	-0.109	0.044					81.5	
1	26.274	-0.141	-0.250	0.791	-0.032	-0.294	0.845	79.6	2.3
2	26.507	-0.144	-0.350	1.023	-0.035	-0.394	0.824	79.9	2.0
3	27.112	-0.109	-0.729	1.628	0.000	-0.773	1.817	76.9	5.7
4	27.735	-0.101	-0.963	2.251	0.008	-1.007	2.103	73.8	9.4
5	28.792	-0.162	-1.179	3.308	-0.053	-1.223	3.528	70.1	13.9
6	29.682	-0.217	-1.313	4.198	-0.108	-1.357	4.414	68.2	18.6
7	30.486	-0.260	-1.418	5.002	-0.151	-1.462	5.216	65.1	20.1
8	31.395	-0.322	-1.578	5.911	-0.213	-1.622	5.890	62.0	25.6
9	32.658	-0.297	-1.760	7.174	-0.188	-1.804	7.401	62.9	22.8
10	33.039	-0.297	-1.852	7.556	-0.188	-1.896	7.793	62.8	22.9
11	32.916	-0.296	-1.709	7.432	-0.187	-1.753	7.638	60.5	25.8
12	33.008	-0.274	-1.689	7.524	-0.166	-1.733	7.724	59.3	27.3
13	32.558	-0.362	-1.639	7.074	-0.253	-1.683	7.278	55.1	32.4
14	33.359	-0.318	-1.735	7.876	-0.209	-1.779	8.077	55.5	31.8
15	33.509	-0.321	-1.801	8.026	-0.212	-1.845	8.238	55.3	32.1

CB-D

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
Initial	25.289	-0.205	-0.345					31.8	
1	25.392	-0.228	-0.404	0.102	-0.023	-0.059	0.126	25.4	19.9
2	25.539	-0.217	-0.449	0.249	-0.012	-0.104	0.271	25.1	20.9
3	25.569	-0.219	-0.456	0.280	-0.014	-0.111	0.301	23.3	26.7
4	25.547	-0.102	-0.687	0.257	0.103	-0.342	0.442	22.3	29.6
5	25.829	-0.085	-0.751	0.540	0.120	-0.406	0.687	22.1	30.2
6	25.754	-0.123	-0.627	0.465	0.082	-0.282	0.550	20.4	35.7
7	25.818	-0.096	-0.655	0.529	0.109	-0.310	0.623	20.0	37.1
8	26.001	-0.086	-0.691	0.712	0.119	-0.346	0.801	21.0	33.8
9	25.939	-0.081	-0.647	0.650	0.124	-0.302	0.728	19.1	39.9
10	26.048	-0.080	-0.707	0.759	0.125	-0.362	0.850	18.7	41.1
11	26.184	-0.119	-0.694	0.895	0.086	-0.349	0.965	18.0	43.4
12	26.352	-0.096	-0.688	1.063	0.109	-0.343	1.122	16.4	48.4
13	26.486	-0.141	-0.676	1.197	0.064	-0.331	1.243	15.0	52.7
14	26.637	-0.113	-0.686	1.348	0.092	-0.341	1.393	14.3	55.0
15	26.639	-0.123	-0.593	1.349	0.082	-0.248	1.375	13.5	57.4

WA-D

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
Initial	24.916	-0.137	-0.267					25.4	
1	24.377	-0.095	-0.022	-0.539	0.042	0.245	0.594	14.6	42.3
2	23.869	-0.122	0.057	-1.047	0.015	0.324	1.098	12.2	51.7
3	23.721	-0.117	-0.061	-1.196	0.021	0.207	1.217	11.0	56.5
4	23.346	-0.001	-0.224	-1.570	0.136	0.043	1.577	9.4	63.1
5	23.640	-0.014	-0.234	-1.276	0.123	0.033	1.283	8.1	68.2
6	23.323	-0.001	-0.092	-1.593	0.137	0.176	1.608	6.9	73.0
7	23.398	0.024	-0.074	-1.518	0.161	0.193	1.541	5.7	77.4
8	23.703	-0.029	-0.253	-1.213	0.108	0.014	1.219	5.1	80.1
9	23.783	-0.049	-0.201	-1.133	0.088	0.066	1.139	4.4	82.6
10	23.605	-0.016	-0.329	-1.311	0.121	-0.062	1.321	3.6	86.0
11	23.697	-0.006	-0.417	-1.219	0.132	-0.150	1.238	2.9	88.8
12	24.343	0.005	-0.604	-0.573	0.142	-0.337	0.765	2.3	90.9
13	24.256	-0.049	-0.712	-0.661	0.088	-0.444	0.822	1.9	92.5
14	24.304	-0.060	-0.710	-0.612	0.077	-0.443	0.875	1.5	94.2
15	24.139	-0.027	-0.791	-0.777	0.110	-0.524	0.953	1.4	94.5

CB3P

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
Initial	25.287	-0.204	-0.396					32.9	
1	25.429	-0.228	-0.441	0.142	-0.024	-0.045	0.152	27.0	17.7
2	25.548	-0.216	-0.481	0.261	-0.012	-0.085	0.275	27.0	17.7
3	25.604	-0.196	-0.521	0.318	0.008	-0.126	0.342	25.7	21.8
4	25.581	-0.104	-0.714	0.294	0.100	-0.318	0.445	24.8	24.6
5	25.643	-0.096	-0.694	0.356	0.108	-0.298	0.478	24.0	26.9
6	25.677	-0.127	-0.676	0.390	0.078	-0.281	0.488	22.9	30.5
7	25.746	-0.087	-0.704	0.459	0.118	-0.309	0.566	21.9	33.3
8	25.808	-0.088	-0.653	0.521	0.116	-0.258	0.593	21.5	34.5
9	25.756	-0.079	-0.608	0.469	0.125	-0.213	0.531	20.5	37.5
10	26.090	-0.078	-0.736	0.803	0.126	-0.341	0.882	20.6	37.3
11	26.196	-0.122	-0.738	0.909	0.082	-0.343	0.976	18.9	42.6
12	26.229	-0.092	-0.751	0.943	0.113	-0.356	1.015	16.5	49.7
13	26.721	-0.161	-0.792	1.434	0.044	-0.396	1.489	16.4	50.2
14	26.795	-0.141	-0.846	1.508	0.064	-0.451	1.576	14.5	55.8
15	26.694	-0.097	-0.761	1.408	0.108	-0.366	1.459	12.7	61.3

SW-3P

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
Initial	25.494	-0.220	-0.133					77.3	
1	25.707	-0.228	-0.188	0.213	-0.008	-0.056	0.221	73.7	4.6
2	25.771	-0.219	-0.251	0.276	0.001	-0.118	0.303	72.8	5.7
3	25.723	-0.202	-0.240	0.228	0.018	-0.107	0.254	74.3	3.9
4	25.650	-0.064	-0.488	0.156	0.156	-0.356	0.420	72.0	6.8
5	25.611	-0.089	-0.412	0.117	0.131	-0.279	0.332	70.8	8.4
6	25.704	-0.109	-0.391	0.210	0.111	-0.258	0.352	70.3	8.9
7	25.664	-0.078	-0.412	0.170	0.142	-0.279	0.357	69.9	9.5
8	25.652	-0.073	-0.386	0.158	0.147	-0.253	0.333	68.5	11.4
9	25.701	-0.071	-0.463	0.207	0.149	-0.330	0.417	67.1	13.1
10	25.575	-0.061	-0.526	0.081	0.159	-0.393	0.433	62.0	19.8
11	25.698	-0.066	-0.582	0.203	0.154	-0.449	0.518	60.7	21.5
12	25.849	-0.104	-0.518	0.355	0.116	-0.386	0.559	58.3	24.6
13	26.215	-0.131	-0.659	0.721	0.089	-0.527	0.901	56.8	26.5
14	26.353	-0.127	-0.604	0.859	0.093	-0.471	0.986	52.5	32.1
15	25.986	-0.084	-0.614	0.491	0.136	-0.482	0.706	50.2	35.0

PPG-3P

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
Initial	25.573	-0.117	-0.228					80.0	
1	25.784	-0.149	-0.263	0.211	-0.033	-0.035	0.218	73.0	8.8
2	27.066	-0.190	-0.495	1.492	-0.073	-0.266	0.280	66.8	16.6
3	25.974	-0.127	-0.371	0.401	-0.010	-0.142	0.426	69.0	13.8
4	26.097	-0.008	-0.652	0.523	0.108	-0.423	0.682	66.1	17.5
5	25.932	0.011	-0.540	0.358	0.127	-0.312	0.492	63.0	21.3
6	26.409	-0.080	-0.619	0.836	0.037	-0.391	0.924	65.1	18.7
7	25.999	-0.016	-0.566	0.426	0.101	-0.338	0.554	61.6	23.0
8	26.063	-0.008	-0.531	0.489	0.108	-0.302	0.586	57.3	28.4
9	26.254	-0.059	-0.553	0.681	0.058	-0.324	0.757	55.2	31.0
10	26.413	-0.030	-0.650	0.840	0.087	-0.422	0.944	54.3	32.1
11	26.521	-0.041	-0.601	0.947	0.076	-0.372	1.021	50.4	37.0
12	27.337	-0.071	-0.732	1.764	0.046	-0.503	1.839	47.9	40.1
13	28.068	-0.132	-0.873	2.495	-0.016	-0.644	2.577	46.2	42.2
14	28.008	-0.114	-0.846	2.435	0.003	-0.618	2.512	43.3	45.9
15	28.209	-0.133	-0.914	2.636	-0.016	-0.686	2.724	40.3	49.7

CB-3F

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
Initial	24.038	-0.252	-0.364					63.8	
1	24.059	-0.238	-0.389	0.021	0.014	-0.025	0.053	60.7	4.8
2	24.027	-0.178	-0.145	-0.011	0.074	0.219	0.234	60.7	5.0
3	24.111	-0.182	-0.308	0.073	0.070	0.057	0.137	60.5	5.2
4	24.092	-0.101	-0.406	0.053	0.152	-0.041	0.192	57.7	9.6
5	24.112	-0.095	-0.510	0.074	0.157	-0.146	0.238	58.2	8.9
6	24.145	-0.095	-0.326	0.107	0.157	0.038	0.205	56.9	10.8
7	24.123	-0.062	-0.282	0.085	0.190	0.082	0.241	57.3	10.2
8	24.090	-0.024	-0.358	0.052	0.228	0.006	0.248	57.0	10.7
9	24.146	-0.018	-0.389	0.107	0.234	-0.024	0.269	57.1	10.6
10	24.302	-0.018	-0.464	0.263	0.234	-0.100	0.374	56.7	11.2
11	24.201	0.026	-0.491	0.162	0.278	-0.126	0.348	57.0	10.7
12	24.382	0.027	-0.421	0.344	0.279	-0.057	0.459	55.9	12.4
13	24.411	-0.007	-0.432	0.372	0.245	-0.068	0.452	55.7	12.7
14	24.408	0.031	-0.441	0.369	0.283	-0.076	0.478	55.3	13.4
15	24.358	-0.004	-0.396	0.320	0.248	-0.031	0.411	55.9	12.5

SW-3F

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
Initial	24.113	-0.108	-0.730					74.6	
1	24.174	-0.094	-0.682	0.061	0.014	0.048	0.084	73.0	2.2
2	24.157	-0.073	-0.673	0.043	0.036	0.057	0.089	73.5	1.5
3	24.182	-0.091	-0.692	0.068	0.018	0.038	0.086	73.5	1.5
4	24.110	-0.019	-0.852	-0.003	0.089	-0.122	0.152	72.1	3.3
5	24.074	-0.031	-0.843	-0.039	0.078	-0.113	0.152	70.7	5.2
6	24.057	-0.058	-0.802	-0.056	0.051	-0.072	0.122	71.1	4.6
7	24.050	0.007	-0.859	-0.063	0.115	-0.129	0.197	70.3	5.8
8	24.061	0.034	-0.803	-0.053	0.142	-0.073	0.169	71.7	3.9
9	24.065	0.039	-0.853	-0.048	0.147	-0.123	0.204	71.4	4.2
10	24.291	0.041	-0.987	0.178	0.149	-0.257	0.357	70.9	5.0
11	24.335	0.061	-1.014	0.222	0.169	-0.284	0.455	72.5	2.8
12	25.257	0.033	-1.168	1.144	0.141	-0.438	1.265	71.0	4.8
13	25.932	-0.067	-1.514	1.818	0.042	-0.784	1.988	71.0	4.8
14	26.148	-0.065	-1.554	2.035	0.043	-0.824	2.198	69.9	6.2
15	24.801	0.037	-1.114	0.688	0.145	-0.384	0.806	70.8	5.0

SW-05PD

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
Initial	25.098	1.486	0.372					63.5	
1	25.182	1.459	0.382	0.084	-0.027	0.010	0.091	66.3	-4.3
2	25.126	1.493	0.448	0.028	0.007	0.077	0.097	66.1	-4.1
3	25.093	1.468	0.467	-0.005	-0.018	0.095	0.103	66.7	-5.0
4	25.091	1.621	0.198	-0.007	0.135	-0.173	0.222	64.4	-1.3
5	25.024	1.607	0.230	-0.074	0.121	-0.142	0.201	64.2	-1.1
6	24.889	1.602	0.323	-0.208	0.116	-0.048	0.245	63.9	-0.6
7	24.966	1.622	0.264	-0.132	0.136	-0.108	0.219	64.1	-0.9
8	24.901	1.628	0.356	-0.197	0.142	-0.016	0.244	63.7	-0.2
9	24.903	1.629	0.309	-0.194	0.143	-0.063	0.251	63.6	-0.1
10	24.902	1.629	0.281	-0.196	0.143	-0.091	0.260	63.5	0.1
11	24.882	1.642	0.249	-0.216	0.156	-0.123	0.296	63.2	0.6
12	24.870	1.719	0.302	-0.228	0.233	-0.069	0.334	63.4	0.2
13	24.994	1.591	0.244	-0.104	0.105	-0.127	0.217	64.2	-1.1
14	24.883	1.616	0.337	-0.215	0.129	-0.034	0.259	63.4	0.2
15	24.848	1.616	0.329	-0.249	0.129	-0.043	0.285	63.0	0.9

SW-04PD

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
Initial	26.618	1.347	0.477					42.3	
1	27.657	1.317	0.045	1.039	-0.029	-0.432	1.127	43.1	-1.9
2	28.652	1.154	-0.241	2.034	-0.193	-0.718	2.171	41.5	1.7
3	29.182	1.204	-0.472	2.564	-0.142	-0.949	2.739	39.5	6.6
4	29.131	1.272	-0.638	2.513	-0.074	-1.115	2.751	35.7	15.7
5	28.923	1.267	-0.508	2.305	-0.079	-0.985	2.508	33.8	20.1
6	29.109	1.223	-0.577	2.492	-0.124	-1.054	2.708	31.3	25.9
7	29.886	1.170	-0.924	3.268	-0.177	-1.402	3.561	32.0	24.5
8	29.582	1.220	-0.717	2.964	-0.127	-1.194	3.200	30.5	27.9
9	30.447	1.151	-1.053	3.829	-0.196	-1.531	4.128	30.8	27.2
10	32.526	0.965	-1.423	5.908	-0.382	-1.900	6.219	30.0	29.1
11	33.075	0.909	-1.489	6.457	-0.438	-1.967	6.765	28.7	32.1
12	32.767	0.984	-1.466	6.149	-0.362	-1.943	6.461	27.5	35.0
13	32.294	1.026	-1.283	5.676	-0.321	-1.760	5.953	26.5	37.6
14	32.842	0.943	-1.519	6.224	-0.404	-1.997	6.550	25.0	41.0
15	31.397	1.034	-1.222	4.779	-0.313	-1.699	5.082	23.3	45.2

Xenon Arc Black

CB-2

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
initial	24.99	-0.18	-0.15	0	0	0	0	38.3	
1	25.15	-0.20	-0.20	0.16	-0.02	-0.04	0.18	36.52	-4.18
2	25.20	-0.20	-0.22	0.21	-0.02	-0.06	0.23	35.50	-7.02
3	25.25	-0.16	-0.29	0.27	0.02	-0.13	0.30	37.99	-0.42
4	25.22	-0.14	-0.30	0.23	0.04	-0.14	0.28	37.04	-3.24
5	25.23	-0.17	-0.25	0.24	0.00	-0.10	0.26	36.77	-3.85
6	25.16	-0.13	-0.32	0.17	0.05	-0.16	0.25	36.62	-4.39
7	25.26	-0.15	-0.37	0.27	0.02	-0.21	0.35	37.18	-3.08
8	25.03	-0.05	-0.42	0.04	0.13	-0.26	0.31	35.97	-6.05
9	25.02	-0.02	-0.43	0.04	0.16	-0.28	0.35	35.30	-7.61
10	25.04	-0.04	-0.42	0.05	0.13	-0.27	0.33	36.47	-4.44
11	24.93	-0.01	-0.40	-0.06	0.17	-0.25	0.34	36.99	-3.17
12	24.88	-0.03	-0.35	-0.11	0.15	-0.19	0.30	35.54	-7.39
13	24.80	0.02	-0.38	-0.18	0.20	-0.22	0.38	36.19	-5.36
14	24.70	-0.03	-0.27	-0.28	0.14	-0.11	0.37	36.39	-4.96
15	24.65	0.02	-0.32	-0.33	0.19	-0.16	0.43	34.30	-10.33

PPG-2

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
initial	25.57	-0.15	-0.05	0	0	0	0	87.77	
1	25.58	-0.16	-0.10	0.01	-0.01	-0.05	0.08	82.79	-5.68
2	25.61	-0.15	-0.13	0.04	0.00	-0.08	0.13	83.82	-4.49
3	25.50	-0.14	-0.19	-0.08	0.00	-0.15	0.18	83.16	-5.25
4	25.49	-0.14	-0.21	-0.08	0.00	-0.16	0.18	85.14	-2.98
5	25.49	-0.14	-0.15	-0.08	0.00	-0.10	0.14	84.61	-3.57
6	25.52	-0.12	-0.25	-0.05	0.02	-0.20	0.22	85.58	-2.48
7	25.50	-0.13	-0.24	-0.07	0.01	-0.19	0.22	85.84	-2.16
8	25.30	-0.02	-0.29	-0.27	0.12	-0.24	0.42	80.77	-7.95
9	25.15	0.02	-0.25	-0.42	0.17	-0.20	0.51	81.01	-7.66
10	25.12	-0.02	-0.18	-0.45	0.13	-0.13	0.51	78.12	-10.98
11	25.76	-0.02	-0.33	0.19	0.12	-0.28	0.38	77.78	-11.34
12	25.75	-0.04	-0.32	0.18	0.10	-0.27	0.61	76.30	-13.06
13	25.98	0.02	-0.40	0.41	0.16	-0.35	1.13	74.50	-15.12
14	26.64	-0.09	-0.39	1.07	0.05	-0.34	1.13	73.46	-16.26
15	26.61	-0.02	-0.32	1.04	0.12	-0.27	1.09	72.68	-17.17

SW-D

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
initial	25.49	-0.23	-0.13	0	0	0	0	78.64	
1	25.66	-0.24	-0.15	0.17	-0.01	-0.03	0.18	77.30	-1.74
2	25.69	-0.30	-0.14	0.20	-0.07	-0.01	0.21	77.22	-1.81
3	25.56	-0.20	-0.16	0.07	0.03	-0.04	0.09	76.04	-3.34
4	25.66	-0.19	-0.27	0.18	0.04	-0.14	0.23	75.96	-3.45
5	25.75	-0.19	-0.25	0.26	0.04	-0.13	0.29	77.78	-1.14
6	25.79	-0.18	-0.32	0.31	0.05	-0.20	0.37	77.67	-1.26
7	25.87	-0.19	-0.40	0.38	0.04	-0.27	0.47	75.82	-3.58
8	25.75	-0.10	-0.45	0.26	0.13	-0.33	0.44	73.14	-6.99
9	25.70	-0.07	-0.47	0.22	0.16	-0.35	0.44	73.97	-5.94
10	25.74	-0.11	-0.38	0.25	0.13	-0.25	0.38	73.89	-6.07
11	25.74	-0.08	-0.46	0.26	0.15	-0.33	0.45	71.31	-9.33
12	25.66	-0.12	-0.39	0.17	0.11	-0.27	0.34	71.42	-9.19
13	25.70	-0.06	-0.46	0.21	0.17	-0.33	0.43	71.42	-9.18
14	25.66	-0.08	-0.38	0.18	0.15	-0.25	0.34	69.60	-11.49
15	25.73	-0.06	-0.46	0.24	0.17	-0.33	0.45	67.82	-13.74

CB-D

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
initial	25.33	-0.22	-0.44	0	0	0	0	29.86	
1	25.42	-0.27	-0.41	0.09	-0.05	0.03	0.11	24.91	-16.57
2	25.57	-0.27	-0.40	0.25	-0.05	0.03	0.25	23.76	-20.38
3	25.68	-0.23	-0.42	0.36	-0.01	0.01	0.36	22.86	-23.47
4	25.76	-0.24	-0.57	0.44	-0.02	-0.14	0.46	24.01	-19.54
5	26.02	-0.22	-0.61	0.69	0.00	-0.17	0.71	23.39	-21.62
6	26.05	-0.21	-0.62	0.72	0.01	-0.18	0.74	23.51	-21.28
7	26.18	-0.20	-0.65	0.85	0.02	-0.22	0.88	23.63	-20.86
8	25.95	-0.12	-0.63	0.63	0.10	-0.20	0.66	21.72	-27.24
9	25.94	-0.08	-0.69	0.62	0.14	-0.25	0.68	21.69	-27.36
10	26.05	-0.09	-0.65	0.72	0.13	-0.22	0.77	20.19	-32.42
11	26.12	-0.11	-0.66	0.79	0.11	-0.23	0.83	20.78	-30.53
12	26.29	-0.15	-0.67	0.96	0.07	-0.23	0.99	20.46	-31.62
13	26.30	-0.10	-0.71	0.98	0.12	-0.27	1.02	19.81	-33.73
14	26.31	-0.13	-0.65	0.98	0.09	-0.22	1.01	20.09	-32.84
15	26.47	-0.14	-0.62	1.15	0.08	-0.19	1.16	19.87	-33.67

WA-D

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
initial	25.09	-0.15	-0.40	0	0	0	0	26.48	
1	25.35	-0.18	-0.39	0.27	-0.03	0.02	0.29	14.04	-46.40
2	25.32	-0.22	-0.39	0.23	-0.06	0.01	0.24	13.52	-48.33
3	25.21	-0.19	-0.47	0.13	-0.04	-0.07	0.18	12.34	-52.85
4	25.59	-0.21	-0.60	0.50	-0.05	-0.19	0.54	11.87	-54.97
5	25.81	-0.27	-0.61	0.72	-0.12	-0.20	0.76	10.71	-59.38
6	25.67	-0.20	-0.67	0.58	-0.05	-0.26	0.64	9.98	-62.21
7	25.93	-0.20	-0.76	0.84	-0.05	-0.36	0.92	9.83	-62.64
8	25.63	-0.12	-0.80	0.55	0.03	-0.39	0.68	8.64	-67.11
9	25.68	-0.09	-0.81	0.59	0.06	-0.40	0.72	8.54	-67.36
10	25.82	-0.09	-0.79	0.73	0.06	-0.39	0.84	7.93	-70.06
11	25.84	-0.08	-0.88	0.75	0.08	-0.48	0.90	7.57	-71.54
12	25.69	-0.11	-0.83	0.60	0.04	-0.42	0.76	7.59	-71.29
13	25.71	-0.02	-0.92	0.62	0.13	-0.52	0.82	7.16	-72.91
14	25.66	-0.13	-0.83	0.57	0.03	-0.43	0.73	6.99	-73.58
15	25.80	-0.07	-1.05	0.71	0.08	-0.65	0.97	6.44	-75.66

PPG-3P

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
initial	25.57	-0.15	-0.27	0	0	0	0	80.76	
1	25.80	-0.14	-0.28	0.22	0.00	-0.01	0.23	76.97	-4.69
2	25.91	-0.17	-0.32	0.33	-0.02	-0.04	0.34	76.84	-4.85
3	25.81	-0.14	-0.32	0.24	0.01	-0.05	0.25	76.22	-5.61
4	26.12	-0.10	-0.48	0.55	0.04	-0.21	0.59	77.16	-4.46
5	26.01	-0.17	-0.34	0.44	-0.03	-0.07	0.44	75.27	-6.79
6	26.07	-0.11	-0.50	0.49	0.04	-0.22	0.54	76.92	-4.74
7	26.10	-0.12	-0.50	0.53	0.03	-0.23	0.58	76.34	-5.45
8	25.87	-0.02	-0.55	0.29	0.13	-0.27	0.42	72.19	-10.60
9	25.91	0.00	-0.58	0.34	0.15	-0.31	0.48	73.63	-8.81
10	25.95	-0.03	-0.53	0.38	0.12	-0.26	0.47	73.88	-8.50
11	25.98	-0.01	-0.60	0.40	0.14	-0.32	0.54	72.03	-10.78
12	26.01	-0.04	-0.53	0.44	0.11	-0.25	0.52	72.62	-10.07
13	25.99	0.01	-0.60	0.42	0.16	-0.32	0.55	71.07	-12.00
14	26.05	-0.03	-0.54	0.48	0.11	-0.27	0.56	72.46	-10.28
15	26.11	0.02	-0.61	0.54	0.17	-0.34	0.66	72.57	-10.15

CB-3F

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
initial	24.22	-0.35	-0.56	0	0	0	0	54.50	
1	24.00	-0.23	-0.35	-0.22	0.13	0.21	0.33	52.42	-3.73
2	24.15	-0.18	-0.24	-0.06	0.18	0.32	0.44	52.88	-2.91
3	24.17	-0.21	-0.28	-0.05	0.14	0.28	0.37	51.20	-6.00
4	24.30	-0.20	-0.28	0.09	0.15	0.27	0.45	53.47	-1.80
5	24.26	-0.15	-0.34	0.04	0.20	0.22	0.36	53.33	-2.13
6	24.34	-0.21	-0.46	0.12	0.14	0.10	0.29	53.18	-2.43
7	24.49	-0.20	-0.42	0.27	0.16	0.14	0.38	52.81	-3.03
8	24.25	-0.07	-0.60	0.03	0.28	-0.04	0.33	51.40	-5.68
9	24.38	-0.05	-0.58	0.17	0.30	-0.02	0.40	51.37	-5.67
10	24.46	-0.07	-0.68	0.25	0.28	-0.12	0.42	51.52	-5.42
11	24.55	-0.01	-0.60	0.33	0.35	-0.05	0.50	51.31	-5.89
12	24.68	-0.06	-0.51	0.46	0.29	0.05	0.55	50.88	-6.62
13	24.63	0.03	-0.51	0.41	0.38	0.05	0.58	51.51	-5.43
14	24.67	-0.03	-0.51	0.45	0.33	0.05	0.57	52.16	-4.29
15	24.66	-0.01	-0.66	0.44	0.34	-0.10	0.59	52.20	-4.25

SW-3F

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
initial	24.23	-0.12	-0.65	0	0	0	0	78.58889	
1	24.33	-0.09	-0.63	0.10	0.03	0.02	0.11	78.26	-0.43
2	24.36	-0.04	-0.53	0.13	0.07	0.12	0.21	79.03	0.59
3	24.34	-0.10	-0.65	0.12	0.02	0.00	0.12	79.00	0.55
4	24.37	-0.05	-0.63	0.14	0.06	0.02	0.16	79.11	0.76
5	24.32	-0.05	-0.61	0.09	0.07	0.04	0.13	78.32	-0.26
6	24.32	-0.12	-0.69	0.09	0.00	-0.04	0.10	78.69	0.19
7	24.37	-0.13	-0.68	0.14	-0.01	-0.03	0.15	78.13	-0.55
8	24.16	0.02	-0.78	-0.07	0.14	-0.13	0.20	76.06	-3.10
9	24.15	0.02	-0.79	-0.07	0.14	-0.14	0.21	75.98	-3.26
10	24.16	0.01	-0.74	-0.07	0.13	-0.09	0.17	75.54	-3.78
11	24.19	0.06	-0.82	-0.04	0.18	-0.17	0.25	76.04	-3.13
12	24.23	-0.04	-0.75	0.01	0.08	-0.09	0.13	74.74	-4.82
13	24.20	0.01	-0.80	-0.03	0.13	-0.14	0.21	74.44	-5.19
14	24.22	0.04	-0.71	-0.01	0.16	-0.06	0.17	74.54	-5.09
15	24.19	0.03	-0.77	-0.04	0.15	-0.12	0.19	74.88	-4.71

SW-05PD

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
initial	25.09	1.47	0.38	0	0	0	0	59.71	
1	25.00	1.49	0.50	-0.09	0.02	0.12	0.16	59.71	0.06
2	24.96	1.47	0.58	-0.13	0.00	0.20	0.24	60.63	1.65
3	25.05	1.50	0.39	-0.04	0.02	0.01	0.06	60.30	1.01
4	25.13	1.47	0.41	0.04	-0.01	0.02	0.20	60.74	1.69
5	25.17	1.48	0.38	0.08	0.00	0.00	0.17	61.44	2.77
6	25.08	1.50	0.36	-0.01	0.03	-0.02	0.05	61.63	3.20
7	25.09	1.49	0.39	0.00	0.02	0.01	0.06	62.10	3.99
8	24.95	1.60	0.30	-0.14	0.13	-0.09	0.23	59.31	-0.83
9	25.01	1.62	0.23	-0.08	0.15	-0.15	0.26	61.20	2.31
10	25.02	1.59	0.28	-0.07	0.11	-0.10	0.20	61.17	2.45
11	25.01	1.61	0.29	-0.08	0.13	-0.09	0.25	61.67	3.16
12	25.02	1.58	0.35	-0.06	0.11	-0.03	0.22	60.39	0.94
13	24.95	1.64	0.32	-0.13	0.17	-0.06	0.27	59.86	-0.02
14	24.93	1.61	0.37	-0.16	0.13	-0.01	0.23	61.47	2.82
15	25.00	1.61	0.29	-0.09	0.14	-0.09	0.19	62.53	4.85

SW-04PD

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
initial	26.34	1.40	0.33	0	0	0	0	52.4	
1	26.54	1.34	0.27	0.19	-0.06	-0.07	0.22	49.43	-5.69
2	26.56	1.33	0.30	0.21	-0.07	-0.03	0.23	51.80	-1.17
3	26.50	1.36	0.27	0.16	-0.04	-0.06	0.18	49.76	-5.03
4	26.65	1.38	0.15	0.31	-0.03	-0.19	0.36	50.19	-4.24
5	26.83	1.30	0.12	0.49	-0.11	-0.21	0.54	49.86	-4.89
6	26.96	1.32	0.05	0.61	-0.09	-0.28	0.68	47.30	-9.75
7	27.05	1.29	-0.03	0.70	-0.12	-0.36	0.80	46.50	-11.27
8	26.90	1.36	-0.10	0.55	-0.04	-0.43	0.70	42.23	-19.41
9	26.82	1.39	-0.09	0.48	-0.01	-0.42	0.64	40.68	-22.43
10	26.83	1.40	-0.01	0.49	-0.01	-0.35	0.60	38.51	-26.51
11	26.98	1.40	-0.11	0.64	-0.01	-0.44	0.78	37.74	-28.01
12	26.88	1.38	-0.01	0.54	-0.02	-0.34	0.64	35.71	-31.84
13	27.07	1.39	-0.16	0.73	-0.01	-0.49	0.88	35.12	-32.96
14	27.10	1.37	-0.08	0.76	-0.04	-0.41	0.86	33.87	-35.35
15	27.14	1.36	-0.12	0.80	-0.05	-0.45	0.92	34.29	-34.67

Xenon Arc Blue

CB-2

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
initial	47.43	-13.86	-28.88	0	0	0	0	48.49	
1	47.68	-14.18	-28.48	0.25	-0.31	0.40	0.57	46.07	-5.04
2	47.74	-14.38	-28.29	0.31	-0.51	0.59	0.84	46.13	-4.80
3	47.80	-14.53	-28.06	0.38	-0.67	0.82	1.12	45.02	-7.15
4	47.80	-14.65	-27.90	0.38	-0.78	0.97	1.31	44.49	-8.26
5	47.88	-14.75	-27.75	0.46	-0.88	1.13	1.51	44.24	-8.55
6	47.92	-14.86	-27.67	0.50	-0.99	1.21	1.64	43.69	-9.99
7	47.91	-14.93	-27.57	0.49	-1.07	1.31	1.76	43.76	-9.69
8	47.96	-15.04	-27.53	0.53	-1.18	1.35	1.87	43.68	-9.89
9	48.01	-15.13	-27.42	0.59	-1.27	1.46	2.02	42.12	-12.89
10	48.04	-15.19	-27.28	0.61	-1.32	1.60	2.17	42.66	-12.14
11	48.13	-15.33	-27.10	0.71	-1.47	1.78	2.41	41.87	-13.80
12	48.02	-15.48	-27.06	0.59	-1.62	1.81	2.50	41.50	-14.52
13	48.17	-15.51	-27.01	0.74	-1.65	1.86	2.60	41.63	-14.22
14	48.23	-15.57	-26.91	0.81	-1.70	1.97	2.73	41.49	-14.36
15	48.28	-15.71	-26.92	0.85	-1.84	1.96	2.82	42.12	-12.90

PPG-2

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
initial	48.61	-13.88	-30.83	0	0	0	0	81.59	
1	48.67	-14.41	-29.93	0.07	-0.54	0.90	1.06	81.54	-0.06
2	48.67	-14.72	-29.51	0.07	-0.85	1.33	1.58	78.33	-4.00
3	48.73	-14.82	-29.18	0.12	-0.94	1.65	1.91	78.11	-4.24
4	48.76	-14.89	-28.94	0.16	-1.01	1.89	2.16	78.67	-3.54
5	48.72	-14.99	-28.87	0.12	-1.12	1.97	2.27	74.51	-8.68
6	48.96	-15.08	-28.69	0.36	-1.20	2.14	2.52	74.12	-9.18
7	49.25	-15.13	-28.46	0.65	-1.25	2.37	2.85	73.47	-9.96
8	49.97	-15.25	-27.94	1.36	-1.38	2.89	3.52	67.54	-17.19
9	49.87	-15.21	-27.78	1.26	-1.34	3.05	3.61	68.59	-15.99
10	49.89	-15.35	-27.56	1.28	-1.47	3.27	3.83	68.88	-15.62
11	50.33	-15.41	-27.22	1.73	-1.54	3.61	4.31	66.97	-17.98
12	50.27	-15.43	-27.23	1.67	-1.56	3.60	4.27	64.68	-20.78
13	52.29	-15.44	-26.17	3.68	-1.56	4.66	6.16	58.87	-27.78
14	51.27	-15.55	-26.39	2.66	-1.67	4.45	5.45	62.09	-23.92
15	50.47	-15.72	-26.79	1.87	-1.84	4.04	4.82	62.04	-24.01

SW-D

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
initial	50.65	-15.91	-30.70	0	0	0	0	70.69	
1	50.70	-16.01	-30.32	0.05	-0.10	0.38	0.40	68.89	-2.54
2	50.68	-16.06	-30.20	0.03	-0.15	0.49	0.52	68.21	-3.50
3	50.65	-16.06	-29.98	0.00	-0.15	0.71	0.73	69.17	-2.15
4	50.65	-16.05	-29.84	0.00	-0.14	0.85	0.87	68.13	-3.61
5	50.64	-16.10	-29.69	-0.01	-0.19	1.00	1.03	67.03	-5.16
6	50.64	-16.07	-29.61	0.00	-0.16	1.09	1.10	67.82	-4.06
7	50.60	-16.05	-29.50	-0.05	-0.14	1.20	1.21	66.53	-5.87
8	50.55	-16.14	-29.30	-0.10	-0.23	1.40	1.42	67.07	-5.11
9	50.62	-16.19	-29.00	-0.02	-0.28	1.70	1.73	66.02	-6.60
10	50.62	-16.21	-28.97	-0.03	-0.29	1.73	1.76	62.89	-11.02
11	50.60	-16.16	-28.94	-0.04	-0.25	1.76	1.78	62.58	-11.47
12	50.79	-16.20	-28.90	0.15	-0.29	1.79	1.86	60.94	-13.78
13	50.66	-16.19	-28.83	0.01	-0.28	1.87	1.89	58.37	-17.42
14	50.65	-16.21	-28.68	0.00	-0.30	2.02	2.04	55.78	-21.08
15	50.66	-16.23	-28.68	0.01	-0.32	2.01	2.04	54.34	-23.11

CB-3P

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
initial	46.60	-12.77	-28.72	0	0	0	0	46.69	
1	46.78	-12.60	-28.59	0.18	0.17	0.13	0.30	43.62	-6.59
2	46.78	-12.60	-28.44	0.18	0.18	0.28	0.38	41.08	-12.02
3	46.82	-12.59	-28.32	0.22	0.18	0.41	0.50	39.76	-14.82
4	46.86	-12.59	-28.21	0.26	0.18	0.51	0.60	40.51	-13.20
5	46.85	-12.53	-28.07	0.25	0.24	0.66	0.75	37.43	-19.92
6	46.88	-12.53	-27.94	0.28	0.24	0.79	0.87	34.60	-25.88
7	46.83	-12.49	-27.76	0.22	0.29	0.96	1.03	36.40	-22.05
8	46.91	-12.51	-27.72	0.30	0.27	1.00	1.08	37.62	-19.41
9	47.03	-12.58	-27.55	0.43	0.20	1.17	1.26	34.16	-26.87
10	46.95	-12.53	-27.51	0.35	0.24	1.21	1.29	32.79	-29.74
11	46.98	-12.48	-27.51	0.38	0.29	1.21	1.31	31.31	-32.99
12	47.06	-12.47	-27.47	0.46	0.30	1.25	1.37	31.73	-31.95
13	47.11	-12.45	-27.45	0.51	0.33	1.27	1.41	31.03	-33.56
14	47.09	-12.51	-27.42	0.49	0.26	1.31	1.42	30.26	-35.19
15	47.19	-12.46	-27.38	0.59	0.31	1.34	1.50	29.67	-36.41

WA-D

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
initial	47.28	-14.01	-30.70	0	0	0	0	21.10	
1	47.29	-14.10	-29.80	0.01	-0.09	0.91	0.92	17.02	-16.96
2	47.33	-14.07	-29.67	0.06	-0.07	1.03	1.04	14.89	-26.41
3	47.40	-13.96	-29.57	0.12	0.05	1.13	1.14	13.53	-32.50
4	47.41	-13.95	-29.42	0.13	0.06	1.28	1.29	12.37	-38.22
5	47.52	-13.92	-29.33	0.24	0.09	1.37	1.40	11.24	-43.41
6	47.59	-13.94	-29.26	0.31	0.07	1.44	1.48	10.04	-49.50
7	47.56	-13.88	-29.20	0.28	0.13	1.50	1.54	10.10	-49.48
8	47.56	-13.98	-29.25	0.29	0.03	1.45	1.49	10.00	-50.13
9	47.60	-13.93	-29.17	0.33	0.08	1.54	1.58	9.71	-52.23
10	47.66	-13.90	-29.03	0.39	0.10	1.67	1.72	9.18	-53.73
11	47.50	-13.86	-28.73	0.22	0.15	1.97	2.00	8.54	-56.57
12	47.49	-14.02	-28.62	0.21	-0.01	2.08	2.10	8.63	-55.93
13	47.57	-13.98	-28.89	0.29	0.03	1.81	1.84	9.21	-53.83
14	47.55	-14.04	-28.86	0.28	-0.04	1.84	1.86	8.70	-56.39
15	47.59	-14.05	-29.05	0.31	-0.04	1.66	1.69	9.21	-53.49

PPG-3P

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE
initial	47.59	-12.94	-30.65	0	0	0	0
1	47.76	-12.82	-30.63	0.17	0.12	0.02	0.22
2	47.66	-12.89	-30.40	0.07	0.05	0.25	0.27
3	47.69	-12.77	-30.11	0.09	0.17	0.54	0.58
4	47.62	-12.79	-29.93	0.03	0.15	0.72	0.73
5	47.67	-12.81	-29.96	0.08	0.13	0.69	0.70
6	47.76	-12.80	-29.74	0.17	0.15	0.91	0.93
7	47.75	-12.79	-29.75	0.15	0.15	0.90	0.93
8	47.70	-12.86	-29.74	0.11	0.08	0.91	0.92
9	47.87	-12.82	-29.62	0.28	0.12	1.03	1.07
10	47.84	-12.79	-29.60	0.25	0.15	1.05	1.09
11	47.88	-12.76	-29.45	0.29	0.18	1.20	1.24
12	47.90	-12.83	-29.46	0.31	0.12	1.19	1.24
13	47.84	-12.81	-29.38	0.25	0.13	1.27	1.31
14	47.92	-12.58	-28.86	0.32	0.36	1.79	1.87
15	47.83	-12.84	-29.37	0.23	0.10	1.28	1.31

CB-3F

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
initial	47.57	-12.67	-29.22	0	0	0	0	51.22	
1	47.64	-12.77	-28.63	0.07	-0.10	0.59	0.61	50.50	-1.35
2	47.61	-12.78	-28.18	0.05	-0.11	1.04	1.05	50.39	-1.67
3	47.61	-12.77	-27.99	0.05	-0.10	1.23	1.24	50.83	-0.80
4	47.64	-12.82	-27.83	0.07	-0.15	1.39	1.40	49.81	-2.73
5	47.68	-12.85	-27.71	0.11	-0.17	1.50	1.52	50.12	-2.28
6	47.73	-12.85	-27.61	0.16	-0.17	1.61	1.63	50.76	-1.01
7	47.69	-12.77	-27.49	0.13	-0.10	1.73	1.74	48.81	-4.76
8	47.69	-12.85	-27.44	0.12	-0.18	1.77	1.79	50.77	-0.92
9	47.79	-12.78	-27.29	0.22	-0.11	1.93	1.95	48.79	-4.69
10	47.79	-12.83	-27.17	0.22	-0.16	2.04	2.06	49.44	-3.44
11	47.77	-12.81	-27.09	0.20	-0.14	2.13	2.14	48.53	-5.29
12	47.77	-12.75	-26.94	0.21	-0.08	2.28	2.29	49.60	-3.17
13	47.78	-12.81	-26.85	0.22	-0.14	2.36	2.38	49.72	-2.85
14	47.82	-12.81	-26.71	0.25	-0.14	2.51	2.52	49.13	-4.05
15	47.85	-12.81	-26.78	0.28	-0.14	2.44	2.46	49.61	-3.08

SW-3F

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
initial	49.63	-17.38	-29.18	0	0	0	0	75.33	
1	49.65	-17.20	-29.45	-0.02	0.00	0.00	0.33	74.70	-0.85
2	49.63	-17.12	-29.45	0.00	0.26	-0.28	0.39	74.53	-1.07
3	49.65	-17.25	-29.45	-0.02	0.00	0.00	0.30	75.33	-0.01
4	49.61	-17.30	-29.43	-0.02	0.08	-0.26	0.27	74.59	-0.99
5	49.58	-17.20	-29.43	-0.05	0.18	-0.25	0.31	75.52	0.28
6	49.61	-17.20	-29.43	-0.02	0.18	-0.25	0.31	75.10	-0.32
7	49.58	-17.32	-29.44	-0.05	0.06	-0.27	0.28	74.21	-1.48
8	49.57	-17.28	-29.46	-0.06	0.10	-0.28	0.31	73.18	-2.85
9	49.56	-17.15	-29.44	-0.07	0.23	-0.27	0.36	72.16	-4.22
10	49.58	-17.27	-29.45	-0.05	0.11	-0.28	0.30	74.83	-0.66
11	49.58	-17.32	-29.44	-0.05	0.07	-0.26	0.27	73.92	-1.88
12	49.58	-17.21	-29.42	-0.05	0.17	-0.24	0.31	74.79	-0.71
13	49.55	-17.25	-29.41	-0.08	0.13	-0.23	0.28	73.74	-2.12
14	49.54	-17.46	-29.44	-0.09	-0.08	-0.26	0.29	74.44	-1.20
15	49.57	-17.42	-29.40	-0.06	-0.03	-0.22	0.23	74.29	-1.39

SW-05PD

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
initial	47.81	-14.48	-28.64	0	0	0	0	70.99	
1	48.09	-14.19	-29.26	0.28	0.28	-0.63	0.74	72.56	2.19
2	48.14	-14.08	-29.23	0.32	0.40	-0.60	0.79	71.28	0.39
3	48.15	-14.16	-29.17	0.34	0.32	-0.53	0.71	68.06	-4.17
4	48.19	-14.19	-29.11	0.38	0.28	-0.48	0.67	69.58	-1.98
5	48.12	-14.11	-29.05	0.30	0.36	-0.41	0.63	65.28	-8.04
6	48.13	-14.06	-28.97	0.32	0.41	-0.34	0.62	66.96	-5.70
7	48.16	-14.21	-28.94	0.34	0.27	-0.31	0.53	65.51	-7.74
8	48.07	-14.26	-29.00	0.26	0.22	-0.36	0.50	63.72	-10.25
9	48.13	-14.06	-28.96	0.32	0.41	-0.32	0.62	62.41	-12.10
10	48.19	-14.15	-28.90	0.38	0.33	-0.27	0.57	63.13	-11.06
11	48.19	-14.22	-28.88	0.38	0.25	-0.24	0.51	60.94	-14.13
12	48.11	-14.15	-28.88	0.29	0.32	-0.25	0.50	59.98	-15.49
13	48.12	-14.22	-28.88	0.31	0.26	-0.25	0.47	57.28	-19.30
14	48.08	-14.33	-28.83	0.27	0.14	-0.19	0.36	55.17	-22.28
15	48.16	-14.22	-28.81	0.35	0.25	-0.17	0.47	55.03	-22.50

SW-04PD

	Ave. L	Ave. a	Ave. b	Ave. ΔL	Ave. Δa	Ave. Δb	Ave. ΔE	Ave. Gloss	Ave. % Change Gloss
initial	49.72	-15.58	-30.29	0	0	0	0	59.19	
1	49.86	-15.33	-30.97	0.14	0.26	-0.68	0.74	61.59	4.14
2	49.83	-15.24	-30.99	0.12	0.34	-0.70	0.79	60.27	1.78
3	49.82	-15.34	-31.01	0.11	0.24	-0.71	0.76	59.32	0.22
4	49.79	-15.34	-30.90	0.08	0.24	-0.61	0.66	59.71	0.94
5	49.71	-15.24	-30.85	0.00	0.34	-0.56	0.66	59.03	-0.24
6	49.71	-15.27	-30.82	-0.01	0.31	-0.52	0.61	60.37	2.06
7	49.72	-15.40	-30.81	0.01	0.19	-0.52	0.56	57.73	-2.31
8	49.72	-15.34	-30.86	0.01	0.24	-0.56	0.62	60.10	1.58
9	49.73	-15.18	-30.83	0.01	0.41	-0.54	0.68	58.40	-1.41
10	49.76	-15.30	-30.78	0.05	0.28	-0.48	0.57	59.96	1.33
11	49.76	-15.37	-30.76	0.05	0.21	-0.47	0.52	59.72	0.88
12	49.72	-15.24	-30.73	0.01	0.35	-0.44	0.57	57.77	-2.45
13	49.74	-15.31	-30.70	0.02	0.28	-0.41	0.50	58.40	-1.31
14	49.71	-15.41	-30.69	-0.01	0.18	-0.40	0.44	57.97	-2.07
15	49.72	-15.33	-30.67	0.01	0.25	-0.38	0.46	58.57	-1.04

Appendix C: Adhesion Values

CB-2 Initial

Sample	Placement	Control Adhesion(PSI)	Type of Failure
A	TOP	926	Cohesive B 80%, Adhesive 5% B/C, Glue 15% Y
	MIDDLE	1026	Cohesive B 90%, Adhesive 5% B/C, Glue 5% Y
	BOTTOM	835	Cohesive B 95% Glue 5% Y
	Ave	929	
H	TOP	730	Cohesive B 95%, Glue 5% Y
	MIDDLE	716	Cohesive B 85%, Glue 15% Y
	BOTTOM	609	Cohesive B 90%, Glue 10% Y
	Ave	685	

CB-2 Final

Sample	Placement	Un-scribed Adhesion(PSI)	Type of Failure
2	TOP	725	Cohesive B 80%, Glue 20% Y
	MIDDLE	664	Cohesive B 100%
	BOTTOM	694	Cohesive B 100%
	Ave	694	
5	TOP	682	Cohesive B 90%, Glue 10% Y
	MIDDLE	665	Cohesive B 95%, Glue 5% Y
	BOTTOM	618	Cohesive B 85%, Glue 15% Y
	Ave	655	
1	TOP	670	Cohesive B 100%
	MIDDLE	631	Cohesive B 100%
	BOTTOM	519	Cohesive B 100%
	Ave	607	

Sample	Placement	Scribed Adhesion(PSI)	Type of Failure
3	TOP	760	Cohesive B 85%, Glue 15% Y
	MIDDLE	745	Cohesive B 97%, Glue 3% Y
	BOTTOM	598	Cohesive B 100%
	Ave	701	
4	TOP	604	Cohesive B 95%, Glue 5% Y
	MIDDLE	752	Cohesive B 100%
	BOTTOM	694	Cohesive B 100%
	Ave	683	

PPG-2 Initial

Sample	Placement	Control Adhesion(PSI)	Type of Failure
H	TOP	1273	85% Cohesive B, 15% Y glue
	MIDDLE	1473	85% Cohesive B, 15% Y glue
	BOTTOM	1464	85% Cohesive B, 15% Y glue
	Ave	1403	
B	TOP	1244	90% Cohesive B, 10% Y glue
	MIDDLE	1297	90% Cohesive B, 10% Y glue
	BOTTOM	1217	85% Cohesive B, 15% Y glue
	Ave	1253	

PPG-2 Final

Sample	Placement	Un-scribed Adhesion(PSI)	Type of Failure
1	TOP	978	75% Cohesive B, Cohesive C 10%, 15% Y glue
	MIDDLE	1200	90% Cohesive B, Cohesive C 5%, 10% Y glue
	BOTTOM		Error in Reading
	Ave	1089	
2	TOP	1040	80% Cohesive B, Cohesive C 5%, 15% Y glue
	MIDDLE	823	65% Cohesive B, Cohesive C 10%, 25% Y glue
	BOTTOM	756	40% Cohesive B, Cohesive C 25%, 35% Y glue
	Ave	873	
5	TOP	839	80% Cohesive B, Cohesive C 10%, 10% Y glue
	MIDDLE	862	80% Cohesive B, Cohesive C 10%, 10% Y glue
	BOTTOM	644	75% Cohesive B, Cohesive C 15%, 10% Y glue
	Ave	782	

Sample	Placement	Scribed Adhesion(PSI)	Type of Failure
3	TOP	764	50% Cohesive B, Cohesive C 10%, 40% Y glue
	MIDDLE	777	70% Cohesive B, Cohesive C 15%, 15% Y glue
	BOTTOM		75% glue
	Ave	770.5	
4	TOP	924	80% Cohesive B, 20% Y glue
	MIDDLE	694	75% Cohesive B, Cohesive C 15%, 10% Y glue
	BOTTOM	787	100% glue
	Ave	809	

WA-D Initial

Sample	Placement	Control Adhesion(PSI)	Type of Failure
J	TOP	1998	99% Cohesive B, 1% Y glue
	MIDDLE	1851	95% Cohesive B, 5% Y glue
	BOTTOM	1996	100% Cohesive B
	Ave	1948	
C	TOP	1928	95% Cohesive B, 5% Y glue
	MIDDLE	2088	95% Cohesive B, 5% Y glue
	BOTTOM	1755	100% Cohesive B
	Ave	1924	

WA-D Final

Sample	Placement	Un-scribed Adhesion(PSI)	Type of Failure
1	TOP	1276	Cohesive B 95%, Glue 5% Y
	MIDDLE	1832	Cohesive B 97%, Glue 3% Y
	BOTTOM	1315	Cohesive B 95%, Glue 5% Y
	Ave	1474	
4	TOP	1618	Cohesive B 95%, Adhesive B/C 5%
	MIDDLE	1340	Cohesive B 95%, Glue 5% Y
	BOTTOM	1069	Cohesive B 90%, Glue 5% Y, Adhesive B/C 5%
	Ave	1342	
5	TOP	1417	Cohesive B 85%, Glue 15% Y
	MIDDLE	1477	Cohesive B 95%, Glue 5% Y
	BOTTOM	1271	Cohesive B 75%, Glue 25% Y
	Ave	1388	

Sample	Placement	Scribed Adhesion(PSI)	Type of Failure
2	TOP	1595	Cohesive B 100%
	MIDDLE	987	Cohesive B 80%, Glue 20% Y
	middle	1387	Cohesive B 45%, Adhesive B/C 5%, 50% glue Y
	Ave	1323	
3	TOP	1635	Cohesive B 93%, Glue 7% Y
	MIDDLE	1282	Cohesive B 80%, Glue 10% Y, Adhesive B/C 10%
	BOTTOM	1271	Cohesive B 100%
	Ave	1396	

CB-D Initial

Sample	Placement	Control Adhesion(PSI)	Type of Failure
B	TOP	1868	Cohesive 90% C, Cohesive 10% B
	MIDDLE	1775	Cohesive 90% C, Cohesive 10% B
	BOTTOM	1654	Cohesive 100% C
	Ave	1766	
G	TOP	1573	Cohesive 99% C, Cohesive 1% B
	MIDDLE	1688	Cohesive 95% C, Cohesive 5% B
	BOTTOM	1632	Cohesive 99% C, Cohesive 1% B
	Ave	1631	

CB-D Final

Sample	Placement	Un-scribed Adhesion(PSI)	Type of Failure
1	TOP	825	Cohesive 90% B, Cohesive 10% C
	MIDDLE	899	Cohesive 100% B
	BOTTOM	1032	Cohesive 100% B
	Ave	919	
2	TOP	1038	Cohesive 75% B, Cohesive 25% C
	MIDDLE	1244	Cohesive 85% B, Cohesive 5% C, Glue Y 10%
	BOTTOM	1471	Cohesive 85% B, Cohesive 15% C
	Ave	1251	
3	TOP	1454	Cohesive 65% C, Adhesive 35% A/B
	MIDDLE	1010	Cohesive85% C, Adhesive 13% A/B, 2% Glue Y
	BOTTOM	1180	99% Adhesion A/B, 1% glue
	Ave	1215	

Sample	Placement	Scribed Adhesion(PSI)	Type of Failure
4	TOP	1243	Cohesive 99% B, Cohesive 1% C
	MIDDLE	1410	Cohesive 50% B, Cohesive 50% C
	BOTTOM	818	Cohesive 100% B
	Ave	1157	
5	TOP	1339	100% Adhesion A/B
	MIDDLE	837	65% Adhesion A/B, 35% Y glue
	BOTTOM	804	69% Adhesion A/B, 30% Cohesion C, 1% glue
	Ave	993	

SW-D Initial

Sample	Placement	Control Adhesion(PSI)	Type of Failure
C	TOP	2596	Cohesive C Top 55%, Adhesive 15% A/B, 30% Y glue
	MIDDLE	2493	Cohesive C Top 30%, Adhesive 30% A/B, 40% Y glue
	BOTTOM	2717	Cohesive C Top 40%, Adhesive 30% A/B,20% Y glue
	Ave	2602	
J	TOP	2702	Cohesive C Top 50%, Adhesive 30% A/B,20% Y glue
	MIDDLE	2487	Cohesive C Top 50%, Adhesive 40% A/B,10% Y glue
	BOTTOM	2018	Adhesive 50% A/B,50% Y glue
	Ave	2402	

SW-D Final

Sample	Placement	Un-scribed Adhesion(PSI)	Type of Failure
1	TOP	2233	Cohesive C Top 15%, Adhesive 5% A/B, 80% Y glue
	MIDDLE	2031	Cohesive C Top 5%, Adhesive 30% A/B, 65% Y glue
	BOTTOM	1767	Cohesive C Top 3%, Adhesive 65% A/B, 32% Y glue
	Ave	1767	
2	TOP	2054	Cohesive C Top 5%, Adhesive 20% A/B, 75% Y glue
	MIDDLE	2317	Cohesive C Top 20%, Adhesive 20% A/B, 60% Y glue failure
	BOTTOM	1340	100% Y glue
	Ave		
3	TOP	2048	Cohesive C Top 30%, Adhesive 25% A/B, 45% Y glue
	MIDDLE	2132	Cohesive C Top 25%, Adhesive 20% A/B, 55% Y glue
	BOTTOM	1557	Cohesive C Top 5%, Adhesive 70% A/B, 25% Y glue
	Ave	1803	

Sample	Placement	Scribed Adhesion(PSI)	Type of Failure
4	TOP	1914	Cohesive C Top 5%, Adhesive 20% A/B, 75% Y glue
	MIDDLE	1625	Cohesive C Top 5%, Adhesive 15% A/B, 80% Y glue
	BOTTOM	1105	100% Y Glue
	Ave		
5	TOP	1205	Cohesive C Top 5%, Adhesive 60% A/B, 35% Y glue
	MIDDLE	1811	100% Y Glue
	BOTTOM	1033	Cohesive C Top 5%, Adhesive 15% A/B, 80% Y glue
	Ave	1205	

CB-3P Initial

Sample	Placement	Control Adhesion(PSI)	Type of Failure
C	TOP	1143	Cohesive B 100%
	MIDDLE	2010	Cohesive B 70%, 30% Cohesive D
	BOTTOM	1848	Cohesive B 80%, 20% Cohesive D
	Ave	1667	
D	TOP	1302	Cohesive B 100%
	MIDDLE	1624	Cohesive B 80%, Glue 20% Y
	BOTTOM	1315	Cohesive B 100%
	Ave	1414	

CB-3P Final

Sample	Placement	Un-scribed Adhesion(PSI)	Type of Failure
2	TOP	766	Cohesive B100%
	MIDDLE	864	Cohesive B 100%
	BOTTOM	766	Cohesive B 100%
	Ave	799	
4	TOP	1070	Cohesive B 100%
	MIDDLE	1117	Cohesive B 100%
	BOTTOM	1208	Cohesive B 100%
	Ave	1132	
5	TOP	1197	Cohesive B 85%, 10% Glue Y, 5% Cohesion C
	MIDDLE	960	Cohesive B 97%, Glue 3% Y
	BOTTOM	990	Cohesive B 95%, Glue 5% Y
	Ave	1049	

Sample	Placement	Scribed Adhesion(PSI)	Type of Failure
3	TOP	831	Cohesive B 100%
	MIDDLE	692	Cohesive B 100%
	BOTTOM	627	Cohesive B 100%
	Ave	717	
1	TOP	898	Cohesive B 100%
	MIDDLE	816	Cohesive B 99%, Cohesive C 1%
	BOTTOM	731	Cohesive B 100%
	Ave	815	

SW-3P Initial

Sample	Placement	Control Adhesion(PSI)	Type of Failure
G	TOP	941	Cohesive B 100%
	MIDDLE	985	Cohesive B 100%
	BOTTOM	1072	Cohesive B100%
	Ave	999	
H	TOP	1165	Cohesive B 100%
	MIDDLE	1048	Cohesive B 100%
	BOTTOM	926	Cohesive B 100%
	Ave	1046	
3	TOP		

SW-3P Final

Sample	Placement	Un-scribed Adhesion(PSI)	Type of Failure
1	TOP	1168	Cohesive B 98%, 2% Glue Y
	MIDDLE	1002	Cohesive B 100%
	BOTTOM	1107	Cohesive B 100%
	Ave	1092	
4	TOP	1175	Cohesive B 99%, 1% Glue Y
	MIDDLE	1252	Cohesive B 97%, 3% Glue Y
	BOTTOM	1184	Cohesive B 100%
	Ave	1204	
5	TOP	1072	Cohesive B 100%
	MIDDLE	1165	Cohesive B 100%
	BOTTOM	824	Cohesive B 100%
	Ave	1020	

Sample	Placement	Scribed Adhesion(PSI)	Type of Failure
2	TOP	1082	Cohesive B 100%
	MIDDLE	936	Cohesive B 100%
	BOTTOM	915	Cohesive B 100%
	Ave	978	
3	TOP	579	Cohesive B 100%
	MIDDLE	684	Cohesive B 99%, 1% Glue Y
	BOTTOM	942	Cohesive B 93%, 7% Glue Y
	Ave	735	

PPG-3P Initial

Sample	Placement	Control Adhesion(PSI)	Type of Failure
D	TOP	2114	Cohesive D Top 95%, 5% Cohesive C Middle
	MIDDLE	2091	Cohesive D Top 90%, 10% Cohesive C Middle
	BOTTOM	1948	Cohesive D Top 100%
	Ave	2051	
F	TOP	2196	Cohesive D Top 100%
	MIDDLE	2239	Cohesive D Top 100%
	BOTTOM	2162	Cohesive D Top 80%, 20% Y glue
	Ave	2199	

PPG-3P Final

Sample	Placement	Un-scribed Adhesion(PSI)	Type of Failure
1	TOP	1425	Cohesive 60% C, Cohesive 30% D, Glue Y 10%
	MIDDLE	1702	Cohesive 90% C, Cohesive 9% D, Glue Y 1%
	BOTTOM		Error
	Ave	1564	
5	TOP	2134	Cohesive 75% C, Cohesive 20% D, Glue Y 5%
	MIDDLE	2267	Cohesive 75% C, Cohesive 20% D, Glue Y 5%
	BOTTOM	1568	Cohesive 80% C, Cohesive 10% D, Glue Y 10%
	Ave	1990	
3	TOP	1983	Cohesive 85% C, Cohesive 10% D, Glue Y 5%
	MIDDLE	2070	Cohesive 85% C, Cohesive 10% D, Glue Y 5%
	BOTTOM	1016	Cohesive 85% C, Adhesive 5% C/D, Glue Y 10%
	Ave	1690	

Sample	Placement	Scribed Adhesion(PSI)	Type of Failure
2	TOP	1857	Cohesive 75% C, Cohesive 10% D, Glue Y 15%
	MIDDLE	861	Cohesive 93% C, Glue Y 7%
	BOTTOM	1917	Cohesive 90% C, Cohesive 5% D, Glue Y 5%
	Ave	1545	
4	TOP	1811	Cohesive 70% C, Cohesive 10% D, Glue Y 20%
	MIDDLE	1522	Cohesive 75% C, Cohesive 5% D, Glue Y 20%
	BOTTOM	2170	Cohesive 75% C, Cohesive 15% D, Glue Y 10%
	Ave	1834	

CB-3F Initial

Sample	Placement	Control Adhesion(PSI)	Type of Failure
C	TOP	714	100% Y glue
	MIDDLE	802	70% Cohesive B, 30% Y glue
	BOTTOM	885	100% Y glue
	Ave	802	
I	TOP	1049	60% Y Glue
	MIDDLE	1035	100% Cohesive B
	BOTTOM	874	95% Cohesive B, 5% Y glue
	Ave	955	

CB-3F Final

Sample	Placement	Un-scribed Adhesion(PSI)	Type of Failure
2	TOP	1093	Cohesive B 98%, Glue Y 2%
	MIDDLE	987	Cohesive B 97%, Glue Y 3%
	BOTTOM	679	Cohesive B 100%
	Ave	920	
3	TOP	1201	Cohesive B 100%
	MIDDLE	1131	Cohesive B 98%, Cohesion C 2%
	BOTTOM	674	Cohesive B 100%
	Ave	1002	
4	TOP	1080	Cohesive B 99%, Glue Y 1%
	MIDDLE	908	Cohesive B 93%, Glue Y 7%
	BOTTOM	975	Cohesive B 100%
	Ave	988	

Sample	Placement	Scribed Adhesion(PSI)	Type of Failure
1	TOP	867	Cohesive B 99%, Glue Y 1%
	MIDDLE	1055	Cohesive B 100%
	BOTTOM	1091	Cohesive B 100%
	Ave	1004	
5	TOP	918	Cohesive B 99%, Glue Y 1%
	MIDDLE	702	Cohesive B 98%, Glue Y 2%
	BOTTOM	870	Cohesive B 100%
	Ave	830	

SW-3F Initial

Sample	Placement	Control Adhesion(PSI)	Type of Failure
I	TOP	978	Cohesive B 100%
	MIDDLE	1016	Cohesive B 100%
	BOTTOM	933	Cohesive B 100%
	Ave	976	
B	TOP	926	Cohesive B 100%
	MIDDLE	1026	Cohesive B 100%
	BOTTOM	835	Cohesive B 100%
	Ave	929	

SW-3F Final

Sample	Placement	Un-scribed Adhesion(PSI)	Type of Failure
1	TOP	742	Cohesive B 100%
	MIDDLE	1231	Cohesive B 100%
	BOTTOM	698	Cohesive B 97%, Cohesive C 3%
	Ave	890	
4	TOP	680	Cohesive B 93%, Adhesive B/C 7%
	MIDDLE	783	Cohesive B 97%, Adhesive B/C 3%
	BOTTOM	592	Cohesive B 97%, Adhesive B/C 3%
	Ave	685	
5	TOP	694	Cohesive B 97%, Adhesive B/C 3%
	MIDDLE	958	Cohesive B 94%, Adhesive B/C 3%, 3% Y Glue
	BOTTOM	801	Cohesive B 94%, Adhesive B/C 3%, 3% Y Glue
	Ave	818	

Sample	Placement	Scribed Adhesion(PSI)	Type of Failure
2	TOP	953	Cohesive B 97%, Adhesive B/C 3%
	MIDDLE	829	Cohesive B 95%, Adhesive B/C 5%
	BOTTOM	661	Cohesive B 90%, Adhesive B/C 10%
	Ave	814	
3	TOP	820	Cohesive B 93%, Adhesive B/C 7%
	MIDDLE	765	Cohesive B 95%, Adhesive B/C 5%
	BOTTOM	878	Cohesive B 95%, Adhesive B/C 5%
	Ave	821	

SW-05PD Initial

Sample	Placement	Control Adhesion(PSI)	Type of Failure
5.4	TOP	781	100% Y GLUE
	MIDDLE	691	100% Y GLUE
	BOTTOM	922	100% Y GLUE
	Ave	798	

SW-05PD Final

Sample	Placement	Un-scribed Adhesion(PSI)	Type of Failure
4	TOP	1308	65% Adhesion A/B, 35% glue Y
	MIDDLE	1301	55% Adhesion A/B, 45% glue Y
	BOTTOM	1144	30% Adhesion A/B, 70% glue Y
	Ave	1251	
2	TOP	848	100% Y GLUE
	MIDDLE	1138	100% Y GLUE
	BOTTOM	1242	100% Y GLUE
	Ave	1076	
1	TOP	1128	100% Y GLUE
	MIDDLE	1493	100% Y GLUE
	BOTTOM	1026	100% Y GLUE
	Ave	1216	

Sample	Placement	Scribed Adhesion(PSI)	Type of Failure
5	TOP	1120	100% Y glue
	MIDDLE	1316	35% Adhesion A/B, 65% glue Y
	BOTTOM	711	2% Adhesion A/B, 98% Y GLUE
	Ave	1049	
3	TOP	1085	100% Y Glue
	MIDDLE	1150	100% Y Glue
	BOTTOM	916	100% Y Glue
	Ave	1050	

SW-04PD Initial

Sample	Placement	Control Adhesion(PSI)	Type of Failure
4.3	TOP	1099	100% Y GLUE
	MIDDLE	1259	100% Y GLUE
	BOTTOM	802	100% Y GLUE
	Ave	1053	
4.10	TOP	1250	100% Y GLUE
	MIDDLE	1681	100% Y GLUE
	BOTTOM	1554	100% Y GLUE
	Ave	1495	

SW-04PD Final

Sample	Placement	Un-scribed Adhesion(PSI)	Type of Failure
5	TOP	397	Adhesive 100% B/C, Tie- to Top-Coat
	MIDDLE	368	Adhesive 97% B/C, 3% glue Y, Tie- to Top-Coat
	BOTTOM	502	Adhesive 100% B/C, Tie- to Top-Coat
	Ave	422	
4	TOP	744	Adhesive 100% B/C, Tie- to Top-Coat
	MIDDLE	507	Adhesive 100% B/C, Tie- to Top-Coat
	BOTTOM	810	Adhesive 100% B/C, Tie- to Top-Coat
	Ave	687	Adhesive 100% B/C, Tie- to Top-Coat
2	TOP	605	Adhesive 95% B/C, 5% glue Y, Tie- to Top-Coat
	MIDDLE	784	Adhesive 100% B/C, Tie- to Top-Coat
	BOTTOM	744	Adhesive 97% B/C, 3% glue Y, Tie- to Top-Coat
	Ave	711	

Sample	Placement	Scribed Adhesion(PSI)	Type of Failure
1	TOP	707	Adhesive 93% B/C, 7% glue Y, Tie- to Top-Coat
	MIDDLE	620	Adhesive 93% B/C, 7% glue Y, Tie- to Top-Coat
	BOTTOM	633	Adhesive 95% B/C, 5% glue Y, Tie- to Top-Coat
	Ave	653	
3	TOP	469	Adhesive 100% B/C, Tie- to Top-Coat
	MIDDLE	668	Adhesive 100% B/C, Tie- to Top-Coat
	BOTTOM	846	Adhesive 100% B/C, Tie- to Top-Coat
	Ave	661	

Appendix D: Specifications/Special Provisions Recommendations

Recommendations to the following special provision and standard specifications are shown in the following appendix. The first section shows the recommended changes for the Special Provision: Railing (Tubular/Steel) (Type) Galvanized. The second section shows recommendations Standard Specification Section 517: Paint and Painting. Finally, the third section shows recommendation to Special Provision: Painting Polysiloxane Systems Structure.

Special Provision Galvanized Railing Recommendations

Railing (Tubular/Steel) (Type) Galvanized X-XX-XXX, Item SPV.0105.XX.

A Description
This special provision describes fabricating, galvanizing, painting and installing railing in accordance with Sections 506, 513 and 517 of the Standard Specifications and the plan details, as directed by the Engineer, and as hereinafter provided.

B Materials
All materials for railing shall be new stock, free from defects impairing strength, durability and appearance. Railing assemblies shall be galvanized and receive a two-coat paint system. Bubbles, blisters and flaking in the coating will be a basis for rejection.

B1 Coating System

B1.1 Galvanizing
Fabricated railings shall meet the requirements of ASTM A385 (i.e. drainage vents, cleanliness, material composition, etc.). After fabrication, blast clean steel railing assemblies per SSPC-SP6 (Note may be an unnecessary procedure) and galvanize according to ASTM A123. Vent holes shall be drilled in members as required to facilitate galvanizing and drainage. Location and size of vent holes are to be shown on the shop drawings. All burrs at component edges, corners and at holes shall be removed and sharp edges chamfered before galvanizing. Condition any thermal cut edges before blast cleaning by shallow grinding or other cleaning to remove any hardened surface layer. Remove all evident steel defects exposed in accordance to AASHTO M 160 prior to blast cleaning. Lumps, projections, globules, or heavy deposits of galvanizing, which will provide surface conditions that when painted, will produce unacceptable aesthetic and/or visual qualities, will not be permitted. Ensure with galvanizing facility that water quenching and chromate or other passivating treatments are not used in the galvanizing process.

B1.2 Two-Coat Paint System
After galvanizing, paint all exterior surfaces of steel railing assemblies and inside of rail elements at field erection and expansion joints as hereinafter provided. All galvanized surfaces to be painted shall be cleaned per SSPC-SP1 to remove chlorides, sulfates, zinc salts, oil, dirt, organic matter and other contaminants.

The cleaned surface shall then be brush blast cleaned per SSPC-SP16 to create a slight angular surface profile per manufacturer's recommendation, minimum 1 mil and maximum 1.5 mils, for adhesion of the tie-coat. Wet storage stain shall be removed prior to blasting per SSPC-SP16. Brush blasting shall be performed at angle of 30 to 60 degrees to the surface, using a lower air pressure, generally no greater than 50 psi, and a softer abrasive (Garnet has been used with success in the past). Steel shot and angular iron blasting grit shall not be used under any circumstances. Brush blast surface sufficiently to produce a matte silver appearance on the surface. Brush blasting shall not fracture the galvanized finish or remove any dry film thickness. Prior to application of tie-coat visible deposits of oil, grease and other

contaminates shall be removed from the surface per SSPC-SP1, and the brush blasted surface shall be cleaned of dust, dirt, and loose residue in accordance to Standard Specification 517.

After cleaning, apply a tie-coat from an approved coating system that is specifically intended to be used on a galvanized surface, per manufacturer's recommendations, and within 8 hours of blasting. The tie-coat shall etch the galvanized rail and prepare the surface for the top-coat. Apply a top-coat per manufacturer's recommendations, matching the specified color shown on the plans. Use a preapproved top-coat that is resistant to the effects of the sun and is suitable for a marine environment. The tie- and top-coats should be of contrasting colors, and come from the same manufacturer.

Ensure that the paint manufacturer reviews the process to be used for surface preparation and application of the paint coating system with the paint applier. The review shall include a visit to the facility performing the work if requested by the paint manufacturer. Provide written confirmation, from the paint manufacturer to the engineer, that the review has taken place and that issues raised have been addressed before beginning coating work under the contract.

Use one of the qualified paint manufacturers and products given below. An equivalent system may be used with the written approval of the Engineer.

Manufacturer	Coat	Products	Dry Film Minimum Thickness (mils)	Min. Time[1] Between Coats (hours)
Sherwin Williams 1051 Perimeter Drive Suite 710 Schaumburg, IL 60173 847-330-1562	Tie	Recoatable Epoxy Primer B67-5 Series / B67V5	2.0 to 4.0	6
	Top	Acrolon 218 HS Polyurethane, B65-650	2.0 to 4.0	NA
Carboline 350 Hanley Industrial St. Louis, MO 63144 314-644-1000	Tie	Rustbond Penetrating Sealer FC	1	36
	Tie	Carboguard 60	4.0 to 6.0	10
	Tie	Carboguard 635	4.0 to 6.0	1
	Tie	Galoseal WB	0.5 to 1	1
	Top	Carbothane 133 LH(satin)	4	NA
Wasser Corporation 4118 B Place NW Suite B Auburn, WA 98001 253-850-2967	Tie	MC-Ferrox B 100	3.0 to 5.0	8
	Top	MC-Luster 100	2.0 to 4.0	NA
PPG Protective and Marine Coatings P.O. Box 192610 Little Rock, AR 72219-2610 414-339-5084	Tie	Amercoat 399	3.0 to 5.0	3
	Top	Amercoat 450H	2.0 to 4.0	NA

[1] Time is dependent on temperature and humidity. Contact manufacturer for more specific information.

B2 Shop Drawings

Submit shop drawings showing the details of railing construction. Show the railing height post spacing, rail location, weld sizes and locations and all dimensions necessary for the construction of the railing. Show location of shop rail splices, field erection joints and expansion joints. State the name of the paint manufacturer and the product name of the tie-coat and top-coat used along with the color. State the size and material type used for all components. Also show the size and location of any vent or drainage holes provided.

C Construction

C1 Delivery, Storage and Handling

Deliver material to the site in an undamaged condition. Upon receipt at the job site, all materials shall be thoroughly inspected to ensure that no damage occurred during shipping or handling and conditions of materials is in conformance with these specifications. Handle coated railing in accordance to Standard Specification 517. If coating is damaged, Contractor shall repair or replace railing assemblies to the approval of the Engineer at no additional cost to the Owner. Carefully store the material off the ground to ensure proper ventilation and drainage. Exercise care so as not to damage the coated surface during railing installation. No field welding, field cutting or drilling will be permitted without the approval of the Engineer.

C2 Touch-up and Repair

For minor damage caused by shipping, handling or installation to coated surfaces, touch-up the surface in conformance with the manufacturer's recommendations, and conforming to ASTM A780. If damage is excessive, the railing assembly shall be replaced at no additional cost to the Owner. The Contractor shall provide the Engineer with a copy of the manufacturer's recommended repair procedure and materials before repairing damaged coatings.

D Measurement

The department will measure Railing (Tubular/Steel) (Type) Galvanized X-XX-XXX as a single lump sum unit for each structure where railing is satisfactorily furnished and installed.

E Payment

The department will pay for the measured quantity at the contract unit price under the following bid item:

ITEM NUMBER	DESCRIPTION	UNIT
SPV.0105.XX	Railing (Tubular/Steel) (Type) Galvanized X-XX-XXX	LS

Payment is full compensation for fabricating, galvanizing, painting, transporting, and installing the railing, including any touch-up and repairs; and for furnishing all labor, tools, equipment, materials and incidentals necessary to satisfactorily complete the work.

Standard Specification 517 Recommendations

Section 517 Paint and Painting

517.1 Description

(1) This section describes furnishing paint materials and applying paint to steel or timber structures, including structural steel, miscellaneous metal or lumber, or timber parts of other structures. This work also includes, unless specified otherwise in the contract, preparing surfaces for painting, applying paint, protecting and drying the paint coatings; protecting traffic and property upon and in the vicinity of the structure; and protecting of all portions of the structure against disfigurement by paint or paint materials.

(2) This section also describes shop cleaning; the furnishing and shop application of a complete epoxy coating system on new structural steel; the field cleaning and repair of surfaces field welded or damaged in shipping, handling and erecting the structural steel; and providing a field-applied urethane top-coat on exterior girders.

517.2 Materials

517.2.1 General Requirements

(1) All coatings or paints shall conform to the requirements specified for the type of coating or paint named.

(2) Furnish factory mixed paint or field mix according to the manufacturer's directions and as the contract directs. Paint shall not be used that is passed manufacturer's recommended shelf life.

(3) Ready-mixed paints shall not settle or cake in the container, but should break up readily with a paddle to a smooth, uniform paint of good brushing consistency that dries without streaking, wrinkling, running, or sagging if painted on smooth, vertical surfaces. Prime and undercoats shall dry to a dull gloss, and finish coats to a full gloss. If required, colors and hiding powers shall equal those of samples the department furnished. Any proportions specified in formulae are by weight, unless indicated otherwise in the requirements for specific paint.

517.2.2 Containers

(1) Generally, paint shall arrive packaged in strong, tight, standard commercial, 5 US standard-gallon capacity metal containers, except for the fractional parts of units. Package the fractional parts in one US standard-gallon capacity metal containers. If mechanical means for mixing and stirring are provided at the job site or painting facility, then the contractor may furnish the paint in 30 gallon or other suitable size metal containers.

(2) Mark each container with the name and address of the manufacturer, the type of paint contained, and the date of manufacture. Use tight-fitting covers on the containers and arrange them so that the inspector may attach wire-lead seals.

(3) Except as specified above for mixing paint mechanically, mix paint on the job in containers with not more than 15 gallons capacity.

517.2.3 Inspection, Sampling, and Testing

(1) Paint sampling and inspection normally takes place at the point of manufacture; the department may sample the paint at the fabricating shop or in the field. The engineer will obtain samples of paints purchased directly by the state, either for approval at their point of manufacture, or at their destination as indicated, either at the time contracts are awarded, or in the invitation for bids.

(2) If inspecting paints at the point of manufacture, the manufacturer shall furnish, if requested, any formulae required to determine the ingredients before making the paints. The manufacturer shall allow the inspector to check the makeup and grinding of paint batches and shall allow test sampling of any or all batches. The manufacturer also shall furnish, if requested, any formulae required to determine specification conformance.

(3) Take representative samples of all ready-mixed paints after thoroughly mixing the paints. Consider one container chosen at random from each lot or batch for each coat, or if a batch or lot exceeds 500 gallons, one container for each 500 gallon increment or fraction thereof, as representative. Take a one-pint sample from the representative container in the inspector's presence. It is the contractor or manufacturer's responsibility to ensure paint mixing occurs in a container that allows sampling of the paint it contains. Take field samples only from paint that is on the job. Take samples in fabricating shops from

containers of paint proposed for the specific bid item of work.

(4) Perform tests according to applicable standard methods of ASTM or AASHTO.

(5) The engineer may waive sampling and testing requirements for quantities of 5 gallon or less of paint of any single formulation required for each project, provided the paint purchased is from stock that demonstrated a satisfactory service record.

517.2.4 Structural Steel Paint-Epoxy System

517.2.4.1 General

(1) The epoxy system consists of a prime or shop coat of organic zinc-rich paint, an intermediate shop coat of high-build epoxy paint, and a protective shop coat of urethane paint.

(2) The contractor shall furnish and apply paints conforming to the requirements of the epoxy system as specified in the special provisions.

517.2.4.2 Coating System

(1) Furnish an epoxy coating system from the department's approved products list for new structural steel. Use a white epoxy and a urethane that matches the color represented by the number the plans show according to Federal Standard Number 595b. Submit product data sheets to the engineer before applying coatings. Ensure that product data sheets indicate mixing and thinning directions; recommended spray nozzles and pressures; minimum drying times for shop and field applied coats; recommended procedures for painting galvanized bolts, nuts, and washers; and a telephone number for technical service.

517.2.4.3 Zinc Coating

(1) Zinc coat the bearing assemblies specified in 506.2.8. Coat any other structural members and parts that require zinc coating according to ASTM A123, after blast cleaning.

(2) High strength bolts, nuts, and washers shall conform to the material requirements of 506.2.5 and be hot-dip zinc coated as specified in 506.2.5.1.

517.2.5 General-Purpose White Exterior Alkyd Wood Primer

517.2.5.1 General

(1) This subsection covers a ready-mixed modified alkyd prime coat used as a primer in a 3-coat system on highway posts. This is a lead free paint.

(2) The paint shall not skin, liver, curdle or thicken materially in the container. It shall brush easily at package consistency and allow lapping without difficulty. It shall conform to or exceed the performance requirements, not necessarily the composition, of Commercial Item Description A-A-2336A.

517.2.5.2 Composition and Properties

(1) Furnish material conforming to the following:

PIGMENT

Percent by weight	49.0%
Titanium dioxide	16.0%
Calcium carbonate, silica/silicates	33.0%

VEHICLE

Percent by weight	51.0%
Soya and tall alkyd resin	24.0%
Aliphatic hydrocarbon solvent	23.0%
Driers and additives	4.0%
Total	100%

FINISHED PAINT TECHNICAL DATA

Generic type	Alkyd Resin, flat finish, exterior primer
Color	White
Gloss or sheen	Flat 0-15 units at 59 F
Dry time	Touch: 4-8 hours
At 77 F, 50% RH	Recoat: 24 hours
Flash point, closed cup	108 F

VOC, Maximum as packaged ..... 2.92 lb/gal
Solids by Volume (percent)..... 56% +/- 2%
Solids by Weight (percent).....74% +/- 2%
Weight per gallon, pounds 3
Coverage ..... 108 sq ft/gal at 4 mils wet, 2.4 mils dry
Clean-up Solvent ..... Mineral Spirits
Type of Cure ..... Oxidation

517.2.6 White Paint for Wood - Intermediate and Finish Coat

517.2.6.1 General

(1) This subsection covers a ready-mixed, ready-to-apply white paint for exterior exposure, used for an intermediate and finish coat in a 3 coat system on marker posts or other wooden structures. This is a lead-free paint.

517.2.6.2 Composition and Properties

(1) Furnish material conforming to the following:

PIGMENT
Percent by weight ..... 48.0% min to 51.0% max
Titanium dioxide..... 38.0% min to 41.0% max
Zinc oxide ..... 16.5% min to 18.5% max
Calcium carbonate..... 40.5% min to 45.5% max
VEHICLE
Percent by weight ..... 49.0% min to 52.0% max
Long oil soya alkyd resin .....32.0% min to 35.0% max
Linseed oil, heat bodied .....29.0% min to 32.0% max
Mineral spirits ..... 32.0% min to 34.0% max
Linseed/tung oil, heat bodied ..... 1.0% min to 2.0% max
Driers and rheology agents..... 2.5% min to 3.5% max
FINISHED PAINT TECHNICAL DATA
Viscosity - Krebs units at 77 F ..... 95 min to 100 max
Drying time ..... 18 hours max
Total solids by weight ..... 82.0% min to 84.0% max
Total solids by volume .....67.0% min to 71.0% max
Weight per gallon..... 11.77 lb/gal min to 12.02 lb/gal max
Gloss at 59 F ..... 80% minimum
Clean-up solvent..... Mineral spirits
Type of cure..... Oxidation

517.2.6.3 Condition in Container

(1) The ready-mixed paint as received shall not liver, skin, lump, or separate, or corrode the container, or contain hard settled pigment. Pigment shall disperse easily in the liquid portion by hand stirring to form a smooth, homogeneous paint, free from lumps, particles, or foreign material.

517.2.7 (Vacant)

517.2.8 Black Paint for Wood - Intermediate and Finish Coat

517.2.8.1 General

(1) This subsection covers a ready-mixed, ready-to-apply black paint for exterior exposure, used for an intermediate and finish coat in a 3-coat system on marker posts or other wooden structures. This is a lead-free paint.

517.2.8.2 Composition and Properties

(1) Furnish material conforming to the following:

PIGMENT
Percent by weight .....40.0% min to 42.0% max

Lampblack
Nephaline Syenite

VEHICLE

Percent by weight ..... 58.0% min to 60.0% max
Long oil alkyd resin ..... 16.0% min to 17.0% max
Linseed oil, heat bodied ..... 17.75% min to 18.25% max
Mineral spirits ..... 23.20% min to 25.60% max
Linseed/tung oil, heat bodied ..... 9.75% min to 10.25% max
Driers and rheology agents ..... 1.40% min to 1.60% max
Fungicide- tetrachloroisophthalonitrile ..... 0.70% min

FINISHED PAINT TECHNICAL DATA

Viscosity - Krebs units at 77 F ..... 95 min to 100 max
Drying time ..... 18 hours max
Total solids by weight ..... 80.0% min to 82.0% max
Total solids by volume ..... 68.0% min to 70.0% max
Weight per gallon ..... 10.27 lb/gal min to 10.52 lb/gal max
Gloss at 59 F ..... 80% minimum
Clean-up solvent ..... Mineral spirits
Type of cure ..... Oxidation

517.2.8.3 Condition in Container

(1) The ready-mixed paint as received shall not liver, skin, lump, or separate, or corrode the container, or contain hard settled pigment. Pigment shall disperse easily in the liquid portion by hand stirring to form a smooth, homogeneous paint, free from lumps, particles, or foreign material.

517.2.9 Brown Stain for Wood

517.2.9.1 General

(1) This subsection covers using a brown stain on rustic wood fences and other similar rustic materials. If the contractor cannot obtain stain conforming to these specifications because of the small quantities required, it may use an equal dark brown semi-transparent oil stain the engineer finds acceptable. This is a lead-free stain.

517.2.9.2 Composition and Properties

(1) Furnish material conforming to the following:

PIGMENT

Percent by weight ..... 11.0% min to 13.0% max
Black Synthetic Iron Oxide ..... 59.0% min to 61.0% max
Dark Brown Iron Oxide ..... 39.0% min to 41.0% max

VEHICLE

Percent by weight ..... 87.0% min to 89.0% max
Linseed oil, raw ..... 69.0% min to 71.0% max
Mineral spirits ..... 25.0% min to 27.5% max
Driers and rheology agents ..... 0.09% min to 0.12% max
Fungicide- tetrachloroisophthalonitrile ..... 0.50% min to 0.75% max
Water repellent: poly-oxo aluminum stearate ..... 2.0% min to 2.5% max

FINISHED PAINT TECHNICAL DATA

Viscosity - Krebs units at 77 F ..... 45 min to 50 max
Drying time ..... 48 hours max
Total solids by weight ..... 76.5% min to 79.0% max
Total solids by volume ..... 70.0% min to 72.5% max
Weight per gallon ..... 8.18 lb/gal min to 8.35 lb/gal max
Clean-up solvent ..... Mineral spirits
Type of cure ..... Oxidation

517.3 Construction

517.3.1 Coating or Painting Metal

517.3.1.1 General

(1) Clean and prepare the surfaces of metal parts before coating or painting.

(2) The contractor or fabricator shall furnish and erect scaffolding, meeting the engineer's approval, to allow steel inspection before and after coating.

(3) Use rubber rollers or other protective devices, meeting the engineer's approval, on scaffold fastenings. The contractor shall not use metal rollers or clamps and other type fastenings that mar or damage freshly coated surfaces.

(4) For all colors, conform to the standard color samples the department furnished, or as specified.

(5) For structural steel, including weathering steel, and miscellaneous metals that will be encased in concrete, apply only zinc-rich primer as specified in 517.3.1.7.2. The contractor is not required to prime or paint welded stud shear connectors and anchor bolts.

517.3.1.2 Weather Conditions

517.3.1.2.1 General

(1) The contractor shall not apply paint if the air is misty or if conditions are otherwise unsatisfactory for the work. Do not apply paint on damp or frosted surfaces.

(2) If coating or painting material under cover in damp or cold weather, it shall remain under cover until dry or until weather conditions allow its open exposure. The contractor shall not perform coating or painting if the metal is hot enough to cause the coating to blister and produce a porous paint film.

517.3.1.2.2 Temperature

(1) Do not expose coated surfaces to temperatures below 35 F until after dry enough for recoating or applying the top-coat.

(2) Do not apply zinc-rich coatings if the temperature of either the air or the steel is below 40 F.

(3) Do not apply epoxy and urethane coatings if the temperature of either the air or the steel is below 50 F.

(4) Do not apply zinc, epoxy, and urethane coatings if temperature of either air or steel is above manufacture's recommendation.

517.3.1.2.3 Humidity

(1) Do not apply the epoxy coating system if the relative humidity is greater than 90 percent, or unless the steel temperature is at least 5 F higher than the dew point temperature.

517.3.1.3 Surface Cleaning

517.3.1.3.1 General

(1) Clean metal surfaces before painting and surfaces in contact because of bolting, removing rust, mill scale, dirt, oil, or grease and other foreign substances. Unless blast cleaning, neutralize all weld areas with a proper chemical and rinse with water, before cleaning.

(2) Blast clean all non-machined surfaces of a casting before machining the casting.

(3) Blast clean all structural steel, including steel encased in concrete.

517.3.1.3.2 Hand and Power Tool Cleaning

(1) If the engineer allows, use metal brushes, scrapers, chisels, hammers, power tools, or other effective means to remove rust, scale, and dirt. The contractor shall not use tools that excessively scar the metal. Remove oil and grease by solvent cleaning according to SSPC-SP 1. Remove all dust or other loose material.

517.3.1.3.3 Blast Cleaning

517.3.1.3.3.1 General

(1) Blast clean metal surfaces to remove mill scale, rust, dirt, and other substances until the specified profile is obtained. Grind or plane flame-cut edges before blast cleaning to remove flame-hardened material as required to ensure that blast cleaning will produce the specified profile. Ensure that corners and re-entrant

angles are adequately cleaned. Remove sand, grit, or shot before painting. Obtain the engineer's approval of the cleaning before painting. Apply paint before rust forms.

517.3.1.3.3.2 Epoxy Coating System

(1) Blast clean all structural steel receiving this coating to a near-white finish according to SSPC-SP 10.

(2) Solvent clean oil and grease on surfaces receiving this coating according to SSPC-SP 1 and blast clean to a near-white finish according to SSPC-SP 10.

(3) Remove all fins, tears, slivers, and burred or sharp edges present on any steel member, or that appears during blasting, by grinding then re-blast the area to a 1.5 to 2.5 mils surface shape.

(4) If using abrasives for blast cleaning, use either clean dry sand, steel shot, mineral grit, or manufactured grit of a gradation that produces a uniform 1.5 to 2.5 mils profile as measured with a department-approved impregnated surface profile tape.

(5) Remove all abrasive and paint residue from steel surfaces with a commercial grade vacuum cleaner equipped with a brush-type cleaning tool, or by double blowing. If using the double blowing method, vacuum the top surfaces of all structural steel, including top and bottom flanges; longitudinal stiffeners, splice plates, and hangers after completing the double blowing operations. Prior to application of primer deposits of oil, grease, and other contaminates shall be removed from surface per SSPC-SP1. Ensure that the steel is free of dust, dirt, and loose residue when applying primer. Apply the primer within 8 hours after blast cleaning.

(6) Protect all freshly coated surfaces from later blast cleaning operations. Brush any blast damaged primed surfaces with a non-rusting tool, or if visible rust occurs, re-blast to a near white condition. Clean the brushed or blast cleaned surfaces and re-prime within the manufacturer’s recommended time.

517.3.1.3.4 Unpainted Weathering Steel

(1) Clean and surface prepare unpainted weathering steel as specified for this steel in 506.3.31.3.

517.3.1.4 Paint Mixing

517.3.1.4.1 General

(1) During use, stir the paint or coatings to keep the solids uniformly suspended. Mix the paint or coatings according to the manufacturer's directions to a smooth lump free consistency, use a high shear mixer. The contractor shall not use paddle mixers or shakers. Perform mixing, as much as it is practical, in the original container and continue until all the metallic powder or pigment is suspended. Equip air container paint pots with agitators.

(2) Insure thorough dispersion of all pigment or solids that settle to the bottom of the container.

(3) Follow manufacture’s recommendation for sweat-in-time and pot life.

517.3.1.4.2 Zinc-Rich Primers

(1) After mixing, strain the coating through a screen with openings no larger than those for a No. 50 sieve. After straining, continuously agitate the mixed primer up to and during the application.

517.3.1.5 Application

517.3.1.5.1 General

(1) Perform painting in a neat and skillful manner. Apply epoxy system coatings by spraying, using conventional or airless spray. Apply the coating smoothly and uniformly so no excess paint collects at any point. Provide a finished surface free of streaks, pitting, wrinkling, or other irregularities.

(2) Use power spraying equipment that applies the coatings in a fine, even spray without adding any thinner. If applying paint with spray equipment, immediately brush it smooth, if necessary, to provide uniform coverage and to eliminate wrinkling, blistering, and air holes.

(3) In cool weather, the contractor may warm the paint to reduce the viscosity. Heat the paint by placing the paint containers in water or on steam radiators.

(4) Thin the paint, if necessary for proper application during cool weather, according to the manufacturer's recommendations.

517.3.1.5.2 Epoxy System

(1) Apply all coating in a neat and skillful manner according to SSPC-PA 1, producing a uniform, even coating.

(2) Transfer or preserve erection marks, for the field identification of members, and weight marks with a compatible paint on zinc-rich primer, or mark with soapstone on an epoxy coated surface.

(3) Apply the coating with the spray nozzles and pressures the coating system manufacturer recommends to attain the specified film thickness. Apply coating to faying, contact, surfaces of bolted shop and field splices.

(4) Depending on site conditions, paint may require additional time beyond that specified in the product data sheets to ensure proper drying before applying a succeeding coat. For maximum time between coats, adhere to the manufacturer's recommendations except, let no more than 60 days elapse between coats.

(5) Determine the dry film thickness by using magnetic film thickness gauges calibrated for dry film thickness measurement according to SSPC-PA 2. The engineer will reject the coating system if minimum dry film thicknesses are less than specified.

517.3.1.6 Paint Removal

(1) The contractor shall remove coating that does not conform to specifications or is unsatisfactory; and thoroughly clean and recoat, or correct the metal at no expense to the department.

517.3.1.7 Shop Painting

517.3.1.7.1 General

(1) If welding structural steel, complete welding before coating the metal. If welding in the fabricating shop and later erecting by bolting, coat it after completing shop welding. Give steel surfaces welded in the field one coat of weldable primer or other department-approved protective coating after shop welding and shop fabrication.

(2) Apply one coat to the surfaces of iron and steel castings, either milled or finished.

(3) Upon fabrication and acceptance, coat pins and pinholes with a plastic or other department-approved coating before removing from the shop.

(4) Remove all dry spray by vacuuming or sanding, if necessary, before shipment.

(5) Do not load material for shipment until the final shop coating cures and inspection is complete. Mark the components, "RECOMMENDED FOR USE", only after completion and approval of loading.

517.3.1.7.2 Organic Zinc-Rich Primer

(1) After cleaning and approval of the entire surface receiving coating by the inspector, apply the primer in a uniform even coating bonded to the metal. Before applying the prime coat, stripe coat all plate edges, outside corners, areas difficult to coat by spray, welds, bolt heads, nuts, and washers with primer by either brush or spray application. Apply succeeding coats as the product data sheet shows.

(2) The organic primer color shall contrast markedly with the blasted surface color. The fabricator shall submit primer color samples to the engineer for approval.

(3) The primer coat shall have a dry film thickness on the bolted friction splices of the main members of not less than one mil or greater than 2.5 mils. Apply a coating of primer, of not less than 3 mils dry film thickness, to the top of the top flange where the stud shear connectors will be welded.

(4) On all other areas, including the outside surfaces of splice plates, ensure that the dry film thickness above the surface profile for the primer coat is 3 mils to 7 mils.

(5) Remove all bolted shop connections before blasting and coating the members. Blast and prime the parts separately then reassemble and torque the bolts fully.

(6) If applying the coating at the required thickness in one coat produces runs, bubbles, or sags, apply the coating in 2, wet, even coats, using a 50 percent overlap with minimum dry or overspray. If excessive coating thickness produces mud cracking, remove the coating back to soundly bonded coating and recoat the area to the required thickness.

(7) In areas lacking in primer thickness, clean the areas with power washing equipment to remove all dirt; then brush the areas with a non-rusting tool, vacuum and recoat.

517.3.1.7.3 Epoxy System Intermediate and Protective Coats

(1) Mask the faying surfaces of bolted field splices and the top of the top flanges where welding the stud shear connectors during coat application. On all other areas including the outside surfaces of splice plates, ensure that the dry film thickness conforms to the following:

1. For the white intermediate coat, 3.5 mils to 8 mils.
2. For the protective coat, sufficient thickness to provide a uniform color and appearance but not less than 3 mil or more than 5 mils.

NOTE: APPROVED COATINGS ALL HAVE MIN 3 MILS AND MAX OF 5 OR 6 MILS FOR PROCTIVE COAT

517.3.1.7.4 Handling Coated Steel

(1) Exercise extreme care in handling the steel in the shop, during shipping, during erection, and during subsequent construction of the bridge. Ensure that protective coat has had sufficient drying time per manufacturer's recommendation prior to handling and shipping. Insulate the steel from the binding chains by engineer-approved softeners. Use padded hooks and slings to hoist steel. Pack diaphragms and similar pieces so that no rubbing occurs during shipment that damages the coating. Store the steel at the job site on pallets or other engineer-approved supports, free of the ground or water, and stabilize to preclude falling or contact between members.

517.3.1.8 Field Painting

517.3.1.8.1 General

(1) After completing erection, including all bolting, welding, and straightening, remove all adhering rust, scale, dirt, grease, or other foreign material as specified for cleaning surfaces in 517.3.1.3.

(2) Coat surfaces inaccessible after erection with the field coats the plans show. If the retouch coating applied to the shop coat dries thoroughly and the field cleaning is satisfactorily complete, then apply the field coats as called for.

(3) If traffic produces visible dust, control the dust, at no expense to the department, as necessary on each side of the site and take necessary precautions to keep dust and dirt off freshly painted surfaces or those awaiting paint.

(4) Complete adjoining concrete work including form removal before applying the last field coat. If concrete operations damage the paint, reclean and repaint the surface.

(5) If the precautions taken to protect the work required in 517.3.3 are inadequate, or the atmospheric conditions cause paint drift to become a problem, the engineer may require that the contractor discontinue spraying until taking adequate precautions or until favorable atmospheric conditions exist.

517.3.1.8.2 Field Repair of Shop Applied Epoxy Systems

(1) Provide a way to inspect structural steel as specified for erecting scaffolding in 517.3.1.1.

(2) Make all field repairs according to the coating supplier's recommendations, supplied to the engineer by the steel fabricator. Field repairs include preparing the surface of damaged or welded areas by blast cleaning, and applying the complete 3-coat system of primer, intermediate coat, and protective coat.

(3) Repair and recoat surfaces, that cannot be accessed after erection, before erection.

(4) After completing erection, including all connections and any bent metal straightening, prepare the steel for repairs. Remove all adhering scale, dirt, grease, form oil or other foreign matter by appropriate means, and blast clean any rusted or uncoated areas to a near-white finish according to SSPC-SP 10. Remove all abrasive and paint residue from steel surfaces by vacuuming or double blowing, except, if double blowing, vacuum the top surfaces of all structural steel, including top and bottom flanges, splice plates and hangers afterward. Brush the coating surrounding the blasted area with a non-rusting tool, and recoat with an organic zinc-rich primer produced by the manufacturer that produced the organic zinc-rich primers used in the shop. These requirements for cleaning, mixing, and applying the coating, shall govern applying coating to repaired areas. Dry film thickness requirements for repair coats are the same as for the shop coats. Ensure proper drying conditions exist between coating applications.

(5) Zinc coat bearings, nuts, and bolts according to the coating system manufacturer's recommendations. This procedure includes removing any residuals that might impair application, and applying a wash primer or tie-coat before the shop coats.

(6) Any temporary attachments or supports for scaffolding or forms shall not damage the coating system. Use support pads of sufficient size on the fascias where using bracing. Repair any damage that occurs from these devices by the above procedures.

517.3.1.8.3 Urethane Top-Coat for Exterior Girders

(1) Field apply a second coat of urethane as a fourth coat to the exterior girder fascias and bottom exterior girder flange surfaces after completing adjoining concrete work, form removal, and repairing field damage as specified in 517.3.1.8.2. Immediately before applying the second coat of urethane, clean 3-coat surfaces to be top-coated using a light water blast and allow them to fully dry. Do not apply paint until the engineer has approved the cleaning.

(2) Apply the urethane top-coat conforming to 517.3.1.2 and 517.3.1.5 except the top-coat may be applied more than 60 days after the first coat of urethane. Use enough urethane to provide a uniform color and appearance, but do not provide less than 1.0 mil or more than 3.0 mils of dry film thickness.

517.3.2 Painting Lumber and Timber

517.3.2.1 General

(1) If painting lumber and timber, unless the contract provides otherwise, prepare the surface; apply, protect, and dry the paint coatings; also, protect traffic and the property upon and in the vicinity of the structure; and protect all portions of the structure against disfigurement by paint or paint materials.

(2) Clean surfaces being painted to ensure they are free from dust, dirt, or other loose or adhering foreign material.

(3) Unless the plans, the specifications, or the contract provides otherwise, apply 3 coats of paint to all surfaces requiring paint, consisting of a prime, second and finish coat, with paint conforming to 517.2 for paint for wood surfaces. Ensure each coat conforms to the type of paint the plans, the specifications, or the contract designates, or as the engineer directs.

517.3.2.2 Weather Conditions

(1) If painting wood surfaces, conform to the general weather conditions specified in 517.3.1.2. Do not apply paint if the air temperature is below 40 F.

517.3.2.3 Paint Mixing

(1) Mix paint as specified in 517.3.1.4.

517.3.2.4 Application

(1) Apply paint as specified in 517.3.1.5.1 and in the following:

(2) If using brushes, apply paint to produce a smooth, uniform, even coating over the wood or previously applied paint and work it into all corners and crevices.

(3) Do not apply the following coat until the previous coat dries throughout, provided, that at least 3 days elapse before applying any later paint coat.

517.3.3 Protection

(1) The contractor shall remain responsible and shall take precautions, during all painting operations, for protecting traffic, parked vehicles, and the property upon and in the vicinity of the structure against damage by paint drift, drops, or spatters; and for protecting all portions of the structure against disfigurement by paint or equipment. The contractor shall also maintain responsibility for protecting the paint coating during the life of the contract as specified for the contractor's responsibility for work in 107.14.

517.3.4 Structure Repainting

(1) The contractor shall clean and repaint existing structures or parts of existing structures as specified in the special provisions.

517.4 Measurement

(1) The department will measure the Painting Epoxy System bid items as a single lump sum unit for each structure acceptably completed.

517.5 Payment

(1) The department will pay for measured quantities at the contract unit price under the following bid items:

ITEM NUMBER	DESCRIPTION	UNIT
517.0600	Painting Epoxy System (structure)	LS

(2) Payment for the Painting Epoxy System bid items is full compensation for surface preparation; for furnishing and applying paint materials; for protecting traffic and property; for field repairs; and for applying a urethane top-coat to exterior girders.

(3) Unless the plans or special provisions specify otherwise, the department will not pay for priming steel encased in concrete; for painting weathering steel as required under 506.3.32; or for painting steel grid floors, steel railing, steel piling and pile shells, steel sheet piling, drains, downspouts, and miscellaneous steel, This work, including surface preparation, furnishing and applying paint materials, and protecting traffic and property, is incidental to the bid items for the various steel components.

(4) The department will not pay for painting timber structures, timber parts of steel structures, and miscellaneous wooden objects. This work, including surface preparation, furnishing and applying paint materials, and protecting traffic and property, is incidental to the bid items for the various lumber and timber components.

Special Provision Painting Polysiloxane Systems

Painting Polysiloxane System B-XX-XXX, Item SPV.0105.XXXX;

A Description

This work consists of steel surface preparation, shop application of the two-coat polysiloxane system, incidental field painting, and repairs to all damaged areas of structural steel in accordance with the pertinent parts of section 517 of the standard specifications and as hereafter provided.

Included in this work is the shop painting of the interior surface areas of the steel box girders and the framing therein. The contractor may, at his option, coat the interior of the box girders using the first two coats of the three-coat epoxy paint system per section 517.2.4 of the standard specifications. If this option is chosen, the following criteria apply:

1. Cover the box girder in storage or erected if exposed to sunlight for more than 30 days.
2. There will be no adjustment in bid price.

B Materials

Furnish a coating system from the department's approved product list consisting of an organic zinc rich epoxy prime coat and a finish coat of polysiloxane having a resin co-reacted or blended with acrylic, epoxy, or urethane resin or combination thereof supplied by the manufacturer of the zinc rich primer. The coatings shall not contain any isocynates or polyisocynates components. The organic zinc rich epoxy primer shall be in accordance with section 517.2 of the standard specification The organic zinc rich epoxy primer application shall be in accordance to sections 517.2 and 517.3 of the standard specification.

The finished color of the Polysiloxane coating for the exterior of structural steel box girders, including all exterior diaphragms and bracing on steel box girder bridges shall match the Federal Standard No. 595B indicated on the plans.

The finished color of the coating for all structural steel on the interior of structural steel box girders, including all diaphragms and bracing on the interior of steel box girders, shall match the Federal Standard No. 595B as follows:

White – #27925

C Construction

Remove all visually evident steel defects in accordance to AASHTO M 160 prior to blast cleaning. When material defects exposed by blast cleaning are removed, restore the blast profile by either blast cleaning or by using mechanical tools in accordance to SSPC-SP11. Mill or grind flame cut edges so the lines are parallel to the length of the plate edge. Grind exterior corners to a 3/32" radius.

Supply the engineer with product data sheets before any coating is applied. The product data sheets shall indicate the mixing and thinning directions, the recommended spray nozzles and pressures, and the minimum drying time for shop or field applied coats. The manufacturer shall

provide the recommended procedures for coating galvanized bolts, nuts and washers. Provide the range of application for temperature conditions and the procedures for re-coat.

Except for the required incidental field finish work including bolted field splices and repair of damaged areas, shop apply the coatings at the following dry film thicknesses:

Organic zinc rich epoxy primer.....4 mils min NOTE: COROTHANE MAX IS 4MIL AND INTERZINC RECOMMENDS 2-3 MIL (NO MAX)
Polysiloxane finish coat.....4 to 8 mils
Total paint system .....8 mils minimum, 13 mils max.

Measure all thicknesses in accordance to SPCC PA 2.

Apply the organic zinc rich epoxy primer in accordance with section 517.3 of the standard specification except that the dry film thickness on the faying surfaces of bolted field splices shall not be less than 2 mils or greater than 2.5 mils. Mask the faying surfaces during application of the finish coat.

Do not apply polysiloxane if the temperature of air or the steel is below 35 F. A mist coating of polysiloxane in accordance to the manufacturer's procedures is recommended to minimize bubbling.

On the interior of box girders, the paint on the top of the bottom flange shall be uniformly dusted with silica sand or other grit material acceptable to the engineer, to create a non-slip walking surface within the interior of the box girders. The silica sand or other approved grit material shall be uniformly applied on the wet film surface of the first interior coat. Blow off any loose, non-adhered sand or grit prior to application of the second interior coat.

The last sentence of paragraph (4) of 517.3.1.5.2 is revised as follows: The maximum time between coats shall be in accordance to the manufacturer's recommendations except that no more than 60 days may elapse between coats of Polysiloxane System with the exception of additional time for field application of the polysiloxane finish coating in areas where incidental painting is required or damage has occurred.

After delivery of the girders to the project site, prior to erecting the girders, visually inspect the girders and clean if necessary of all dust, dirt, road salts and other contaminants that have collected and adhered on the surfaces of the girders during shipping to the project site. Clean by use of a low-pressure water blast or other means acceptable to the engineer to remove all visually identifiable contaminants, without damage to the shop-applied girder paint.

Take special care during construction to minimize the number and size of touch-up spots. Follow the manufacturer's recommendations for damaged area repairs. The engineer must approve the field paint appearance prior to final acceptance.

Protect the property in the vicinity of the structure from paint over-spray damages for the completion of incidental field painting such as field splices and repair of all damaged areas in accordance to 517.3.1.8. Prior to applying the polysiloxane field coating, clean all primed surfaces and/or areas to be re-coated with light water blast and prepare surfaces as per manufacturer's recommendations. Prior to painting, all surface cleaning and application procedures shall be approved by the engineer.

D Measurement

The department will measure Painting Polysiloxane System (Structure) as a single lump sum unit for each structure acceptably completed.

E Payment

The department will pay for the measured quantity at the contract unit price under the following bid items:

ITEM NUMBER	DESCRIPTION	UNIT
SPV.0105.XXXX	Painting Polysiloxane System B-XX-XXX	LS

Payment is full compensation for steel preparation, for furnishing and applying the paint materials, for protecting the site, for incidental field painting and repairs of damaged areas; and for furnishing all labor, tools, equipment, and incidentals necessary to complete the work.

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