Evaluation of Different Paint Systems for Over-Coating Existing Structural Steel

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16. Abstract

The project was undertaken to identify a procedure to accept new coating systems for over-coating of steel surfaces. The practices used by various state transportation agencies, and test methods for accelerated testing of coatings with primary focus on ASTM and FHWA guidelines were reviewed. It was concluded that a new protocol for accepting new systems that will provide results in a timely manner is required. Therefore, a new protocol for evaluating durability of coatings and their effectiveness in reducing corrosion of steel structures was developed. Results presented in this report focuses on the details of the new protocol, recommendations for acceptance and a plan for implementation. Basic parameters of relevant ASTM specifications and guidelines provided in FHWA publications are incorporated in the test method. The major difference between the proposed method and the current practice is the way the corrosion creep from a coating-damaged location is measured after exposure to accelerated corrosive conditions. The proposed method is based on direct pull-off (adhesion) strength at various stages of corrosion. These pull-off strengths provide quantitative and repeatable measurements for quantifying the degradation. In the area of accelerated exposure conditions, deep freezing is incorporated as part of the accelerated degradation process. These two measures provide significant and clearly measurable degradation within three months of accelerated exposure. Coatings that are known to provide excellent and weak corrosion protection were tested using the proposed protocol and the results show a clear difference between the best and the poor coatings. The test results also correlate well with results of the long-term field study. As expected, corrosion creep from a damaged-coating location is the primary contributor to degradation of coatings. Other degradation indicators such thinning, color change, influence of welding and bolt hole locations were also evaluated. Acceptance criteria for these degradation mechanisms are also incorporated in the acceptance criteria. In the area of quality assurance, this study evaluates correlation coefficients for structural steel paints by performing Infra-Red (IR) scan using ASTM specifications E 2937. Chemical signatures have established for the components of six coating systems that are currently approved for use by New Jersey Department of Transportation (NJDOT).

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EXECUTIVE SUMMARY

The project was undertaken to identify a procedure to accept new coating systems for over-coating of steel surfaces. The practices used by various state transportation agencies, and test methods for accelerated testing of coatings with primary focus on American Society for Testing Materials (ASTM) and Federal Highway Administration (FHWA) guidelines were reviewed. It was concluded that a new protocol for accepting new systems is needed. This new protocol should provide results in a timely manner, preferably within nine months and it should be reasonably economical to conduct the tests. Therefore, a new protocol for evaluating durability of coatings and their effectiveness in reducing corrosion of steel structures was developed. Results presented in this report focuses on the details of the new protocol, recommendations for acceptance criteria and a plan for implementation. Basic parameters of relevant ASTM specifications and guidelines provided in FHWA publications are incorporated in the test method. The major difference between the proposed method and the current practice is the way the corrosion creep from a coating-damaged location is measured after exposure to accelerated corrosive conditions. The proposed method is based on direct pull-off (adhesion) strength at various stages of corrosion. These pull-off strengths provide quantitative and repeatable measurements for quantifying the degradation. In the area of accelerated exposure conditions, deep freezing is incorporated as part of the accelerated degradation process. These two measures provide significant and clearly measurable degradation within three months of accelerated exposure. Coatings that are known to provide excellent and weak corrosion protection were tested using the proposed protocol and the results show a clear difference between the best and the poor coatings. The test results also correlate well with one of the long-term field study. As expected, corrosion creep from a damaged-coating location is the primary contributor to degradation of coatings. Other degradation indicators such as thinning, color change, influence of welding and bolt hole locations were also evaluated. Acceptance limits for these degradation mechanisms are also incorporated in the acceptance criteria. A methodology for quality assurance of the accepted products during their use is also presented. This methodology is based on the current New Jersey Department of Transportation (NJDOT) procedure used for coatings and admixtures. The following are the key conclusions and recommendations:

- The effectiveness and acceptability of new coating system can be determined within six months.
- The new test protocol provides clear quantitatively measurable results for evaluating corrosion vulnerability.
- The results obtained using accelerated corrosion exposure in the laboratory correlate well with the 20-year field-study results conducted by NJDOT (Mathis Bridge).
- Creeping of corrosion from a damaged or weak coating location is the primary contributing factor for degradation of coating systems.
- Among the coating systems currently available in the market, those containing an inorganic zinc or organic zinc primer provides the best performance.
- The epoxy systems and aluminum-mastic systems performed worst

It is recommended to implement the new protocol for accepting any new coatings and at the same time seek support from FHWA and other state DOTs for wider application of the protocol. An efficient way to attain the acceptance by other states is to conduct a broader study with multi-state and laboratories participation. This could be achieved using a pool-fund study. A plan for the implementation is also included in this report. In the area of quality assurance, this study evaluates correlation coefficients for structural steel paints by performing IR scan using ASTM specifications C494-05a. The intent of this study is to perform a sufficient number of scans from different batches of the same sample as supplied by the manufacturer to establish baseline correlation values of individual steel paints. These scans are then analyzed using statistical methods and the correlation coefficients for the steel paint systems were established. These correlation values will be used as quantitative measures to interpret, accept or reject job samples. A total of six structural steel paint components used by NJDOT were tested. They include primary coats, secondary coats, thin films, and others. The results of this study include methodology, test procedures, scan data, and correlation coefficients for quantitative assessment of the most commonly used structural steel paints on the qualified producer/supplier QPL NJDOT list

BACKGROUND

A common practice for maintaining and repairing existing structural steel is to apply an epoxy mastic urethane overcoating. The Society for Protective Coatings (SSPC) defines this practice as follows:

> Overcoating is defined as the application of coating materials over an existing coating in order to extend its service life, including use of the appropriate cleaning methods. The procedure includes preparation of rusted or degraded areas, feathering edges of existing paint, low-pressure water washing of the entire structure to remove contaminants, application of a full intermediate coat over repaired areas, and optional application of a full topcoat over the entire structure [41].

Prior to 2016 NJDOT approved new systems for overcoating based on the evaluation and recommendation of NEPCOAT. This organization discontinued their test program. This project was undertaken to identify acceptance criteria for new over-coating systems. If practices currently used by other agencies including various department of transportation are not satisfactory, a new test protocol was to be developed for use by New Jersey Department of Transportation (NJDOT). The decision to develop a new test procedure was made by NJDOT panel after the research team presented the current state of the art and the need for a new method. The primary weaknesses of the current practice are the time and effort needed to evaluate new coating systems and the difficulty in measuring the outcome after exposure to accelerated corrosion. If a new test method is proposed, it had to be validated and incorporated in the proposed new acceptance criteria. In addition, a plan was to be presented for implementation of the findings.

Infrared (IR) spectroscopy was identified as an effective tool for quality assurance. The IR spectroscopy is typically used for the following cases: 1) the sample (or spectrum) is a "total unknown" and an identification is required – examples include forensic samples, environmental waste samples, or new discovery samples, where a new material has been synthesized or discovered, 2) the sample (or spectrum) is an unknown and it needs to be characterized or classified – examples include commercial applications where new additives or components are included in a material to provide a specific property; in such cases this could be considered the basis of competitive product analysis, 3) the sample generally is known but the existence of a specific chemical class needs to be determined –examples include contaminant analysis, analysis for toxicology or environmental reasons, material additives, etc., and 4) the sample is a complete known and the interpretation is required to confirm the material composition and/or quality – examples include product quality control and the confirmation of a structure or functionality of a newly synthesized material.

The work in this project focused on scenario 4, where the samples are known, and quantitative assessment and quality control were required. Chemical signatures of all the components for 6 currently used systems were obtained for checking future supplies.

OBJECTIVES

The primary objective was to develop a protocol for accepting new systems for over-coating. NJDOT discontinued using NEPCOAT recommendations for accepting new coatings in 2016. Therefore, an efficient and fair protocol was needed for accepting new coating systems in the list of "Approved Coatings". This primary objective can be divided into following secondary objectives:

- Review practices used by other states and other agencies to prepare a summary of current practices.
- Recommend a protocol, that is based on the current practices used by other state DOTs or agencies, for accepting new coating systems to NJDOT panel. If none of the current practice is acceptable, propose a new protocol/test method outlining the strengths of the proposed test and obtain approval for evaluating the proposed test.
- Prepare details of the test program and obtain suggestions/modifications from the NJDOT Panel.
- Evaluate the proposed test method using four to six currently used coating systems.
- Present the results obtained using the proposed test method to the Panel with recommendations and if the test is successful, prepare the acceptance criteria.
- Prepare an implementation plan.
- Provide meaningful interpretations of the IR Scans of structural steel paints and establish correlations for IR scans of manufacturer samples.
- Establish acceptability criteria and determine acceptable tolerances for job samples compared to manufacturer acceptance samples on the NJDOT qualified producer/supplier (QPL) list.

These objectives were to be achieved in two phases. In Phase 1, the primary focus was on Literature Review resulting in a summary and recommendation to adopt an existing protocol or propose a new protocol. If the NJDOT Panel approves, conduct Phase 2 that will focus on evaluating the proposed test method, developing an acceptance criterion and preparing an implementation plan.

Phase I – Literature Review

Phase II – Research Work plan
Task 1 - Selection of potential test methods to be used for acceptance criteria
Task 2 - Evaluation of potential test methods for their suitability for inclusion in acceptance criteria
Task 3 - Development of protocols for accepting new products
Task 4 - Develop guidelines for surface preparation and coating application
Task 5 - Prepare IR Scans for six systems that are currently used
Task 6 - Prepare an implementation plan

INTRODUCTION

A common practice for maintaining and repairing existing structural steel is to apply an epoxy mastic urethane overcoating. NJDOT has an active over-coating program, a typical application example is shown in Figure 1.

Figure 1. An Over-coated beam: US Route 202 over NJ Route 29 before and after Over-coating

Overcoating offers significant advantages over repainting a structural steel bridge. The principal advantage is cost. According to an FHWA article [21], full removal of paint can cost as much as $35 per square foot, because the old paint typically includes lead, which is a hazardous material to humans and the environment. In contrast, overcoat applications can cost an agency in the order of $6 to $10 per square foot. However, overcoating may be susceptible to poor performance based on several factors. According to a FHWA technical note [21], original construction of structural steel bridges incorporated single component oil-alkyds containing lead or lead/chromate pigmentation. Over the years, environmental exposure resulted in alkyds becoming brittle and inflexible, with heavily chalked areas occurring where exposed to direct sunlight. This aging and deterioration, results in poor adhesion of the original paint system on structural steel.

In addition to the original coat system, bridges constructed over 40 years ago were fabricated from steel covered in millscale. In the short-term, millscale provided bridges with corrosion protection. However, as moisture and chlorides penetrated the millscale layer, the millscale itself would help accelerate electrochemical processes corroding the bare steel. The millscale also served as a poor surface for coating adhesion. The presence of millscale can greatly increase the risk of corrosion failure in the rehabilitated structural steel when using overcoating.

Lastly, surface conditions can greatly affect the performance of coating systems. In-service, bridges are exposed to a variety of environmental and industrial pollutants, as well as dirt and debris over their life. The presence of these pollutants and debris build-up result in contamination that must be removed prior to overcoating. Paint performance will be affected by the surface conditions during application. Overcoating performance will be dependent on the underlying layer, and poor conditions will likely result in failure of the coating.

Environmental condition Paint coating performance requirements are listed in Section 24 of the Bridge design manual. Four environmental zones are identified in the State of New Jersey:

- Zone 1 - Rural or industrial, mild exposure. Where severe corrosion is not a problem.
- Zone 2 - Industrial, severe exposure. Area where corrosion is a serious problem. Progressively aggressive industrial locations.
- Zone 3A - Marine, mild exposure. Structural steel more than 15 feet above mean high water. Structure located in less severe coastal salt intrusion zone.
- Zone 3B - Marine, severe exposure. Structural steel less than 15 feet above means high water. Structure located in severe coastal salt intrusion zone.

The NJDOT standard specifications for bridges and structures, section 912.01.01 (3) indicates that only a few paint systems are acceptable under approved method of overcoating existing structural steel. In order for a paint system to be approved for use by NJDOT, the supplier must complete the appropriate Materials Approval Procedure (MAP) and obtain acceptance. Prior to 2016, Northeast Protective Coating Committee (NEPCOAT) was chosen by NJDOT for approving new coating systems. The approved coating systems for existing steel structures as of 2016 are presented in Table 1.

Table 1 - Excerpt from NJDOT Bridge Design Manual Table 24.3 Coating Systems

Coating System	Paint System	Surface Preparation	Acceptable Environmental Zones	Selection Criteria
OEU	P: Organic Zinc Rich I: Epoxy Polyamide F: Aliphatic Urethane	Near-White Blast Cleaning, SSPC-SP-10	All	Use for all existing structural steel with an ASTM D610 Rust Grade of 6 or less and when no major structural work involving steel replacement is scheduled in the near future
EU	P: Aluminum Epoxy Mastic I: Aluminum Epoxy Mastic F: Aliphatic Urethane	Hand/Power Tool Cleaning, SSPC-SP-2/3 (with spot Commercial blast SSPCSP- 6 if and where directed)	All	Use for the painting of all existing structural steel with an ASTM D610 Rust Grade greater than 6.
Key: P=Primer, I=Intermediate, F=Finish				

The current project was initiated to identify and if needed, develop an efficient procedure to provide approvals by NJDOT. The details of this investigation are presented in this report. At the end of the literature search and analysis, it was determined that a new protocol for accepting new coatings is needed. A new protocol that is economical and needs less than nine months was developed. Details of this protocol including experimental set-up, acceptance criteria and plan for implementation are presented in this report.

NJDOT Standard Specifications for Road and Bridge Construction Sections 903.02.01, 903.02.02 and 912.01.01 require the uniform quality assurance testing and approval of structural steel paints. Testing is performed to ensure that contract materials are not adversely modified or altered. Infrared Spectrophotometry Scan (IR Scan) is one of the test methods used to verify that the material sampled and tested from a contract roadway construction or job site is identical to that material originally submitted, approved, and listed on the qualified producer/supplier list.

There is a need to provide accurate and meaningful interpretations of the differences in IR spectra between various batches of structural steel paints delivered to the department and those originally submitted, approved, and listed on the qualified producer/supplier list. At this time, it is not well known what causes these differences, or what is the potential effect on the properties of steel when using paints with non-conforming spectra. Potential reasons for the non-conforming spectra are numerous, e.g., change in formulation, presence of contaminants, improper storage, improper labeling, etc. It is important to ascertain the nature of the problem, understand and interpret the various spectra, and establish acceptability criteria.

The UV-VIS (ultraviolet-visible) spectroscopy and the Raman spectroscopy are two spectroscopic methods used to identify the nature and the concentration of substances causing the nonconformity of IR Scans of certain batches of materials. They are complementary in nature, and when combined with the incoming IR Scan analysis, it should be able to yield complete information regarding the qualitative and quantitative composition of NJDOT approved structural paints.

The purpose of this research is to establish quantitative acceptability criteria and tolerances for job samples tested with respect to manufacturer acceptance samples on the qualified producer/supplier list (QPL) in order to minimize the non-conformity and performance deviation of those materials used in construction projects and on job sites in New Jersey.

Developing a reference spectral library for the selected materials on the NJDOT QPL list will also be beneficial to identify the components in a spectrum of unknown materials using high resolution spectrometers. Such a library would include the spectra for selected materials specified by the NJDOT. The spectral library approach is useful for identifying material types, determining the ranges of spectra and associated optical properties and concentrations. It will be the start of a database of spectra, enabling generic algorithm development and testing. A well-documented spectral library has permanent value and benefits. However, establishing such a library was not part of the scope of this research.

SUMMARY OF LITERATURE SEARCH

Existing literature on coatings for steel surfaces were reviewed with primary focus on acceptance criteria used by the various state Department of Transportation (DOT) authorities for new coating systems for overcoating. Other focus areas were:

- Accelerated test methods used for evaluating coating systems
- Studies on filed performance with particular emphasis on bridge structures
- Correlation of laboratory and field performance and
- Practices of related industries such as automobile and marine industries.

Practices of all the 50 State DOTs and the publications of Federal Highway Administration(FHWA) were reviewed. In addition, the publications available in the literature were also reviewed. For the accelerated testing, the related ASTM standards were evaluated in detail.

Summary of the findings is as follows:

Very few states distinguish between the new and overcoating for the selection of coating systems. Prior to 2016, NJDOT used the recommendations of NEPCOAT for accepting new coating systems. To the best of the author's knowledge, this is the only extensive evaluation method used for selecting overcoating. The test protocol used by NEPCOAT, summarized in the following sections, was subjective and time consuming but did not include the evaluation of the coating from a weak or pre-damaged location which is the primary degradation mechanism identified in the literature.

NEP·OVER·COAT is a Three-Year Field Testing Program

A NEPCOAT committee was formed for qualifying and accepting coating products for maintenance over-coating of previously painted existing steel bridges. The committee had members from the states of: Connecticut (CT), Maine (ME), Massachusetts (MA), New Hampshire (NH), New York (NY), New Jersey (NJ), Pennsylvania (PA), Rhode Island (RI) and Vermont (VT). Corrosion Control Consultants & Labs, Inc. conducted the testing program, including surface preparation, coating application, and performance evaluations. The States provided salvage steel beams for testing at the following sites: Farmington, ME, Scarborough, ME, New Haven, CT, and New Castle, PA.

Each product was applied to these surfaces: (a) intact existing coating; (b) surfaces hand tool cleaned (SP2) with chisel, wire brush, and scraper; (c) surfaces power tool cleaned (SP3) with needle gun, roto-peen, 3M Scotch-Brite™ Clean and Strip disk sander; (d) surfaces cleaned to SP11 condition with roto-peen; and (e) chloride-contaminated pre-rusted metal bar welded to the test beam and cleaned half to SP2 and half to SP3. All surfaces were first power washed at 3,500 psi with a rotating zero-degree nozzle and offset 4-6 inches from the surface. Each test panel was scribed (surface f). During the winter months all test patches were sprayed with 1% salt water. A roof shelter was built over half of the test panels. Details of various surface cleaning methods are presented at the end of this section.

All the coatings were applied by brush and roller (no spray) and according to manufacturer's recommendations. The acceptance criteria included the average results from all four state sites. The requirements were:

• Surfaces (a)(b)(c)(d)(f) must receive a minimum rating of 9 out of 10 (Farmington, ME site excluded from (a)(b)(c)(f)), for surface (d) only the sheltered panels were included) and
• Power tool cleaned side of surface (e) must receive a minimum rating of 6.5 out of 10 (New Castle, PA site excluded).

The suitability of applying the coating by brush and roller was noted but not required for acceptance. The final appearance was noted. Systems varied on gloss and color retention, and presence of brush and roller marks.

Coating Systems Used by Other State DOTs

The following is a short summary of studies conducted by four states for overcoating. None of the studies provide a clear guideline for accepting new coatings.

Missouri Department of Transportation employs two strategies for coating bridges in the field [31]. They are internal coating program and a contract maintenance coating program. The internal coating program utilizes calcium sulfonate alkyd(CSA) to overcoat deteriorated coatings. Contract maintenance system also uses CSA for over coating except that they use additional System G (blast cleaning and application of zinc rich primer). Calcium sulfonate alkyd is used as they perform very good in terms of corrosion protection. Calcium sulfonate alkyd also has some limitations apart from its benefits. One of the main constraint is that they tend to dry slowly and tend not to dry hard as epoxy and urethane systems do. The most important characteristics of a good over-coating system is penetration, wetting, adhesion, minimum shrinkage stress and flexibility. System S and System G coatings are currently used in Missouri. Out of these System G coatings show better field performance.

Virginia DOT conducted filed evaluation of six coating systems consisting of: epoxies, polyurethanes and low-VOC alkyds, for over-coating [39]. Coatings were evaluated using bridge structures. Mill scale, chlorides on the surface, brittleness of the existing coating were found to be the key factors for the over-coating failure. The dry film thickness of the existing coating can be measured easily using magnetic gage. The over-coat system should have low viscosity and high wetting properties.

Kentucky Transportation Cabinet(KYTC) along with Kentucky Transportation Center(KTC) did experiments on I-64 bridges, I-71 bridges and KY-22 bridges [27]. All these three bridges had aged alkyd paint systems applied over mill scale. The main objective for the experiment was to find the over-coat system which lasts for a short duration with minimum cost.

New Jersey Department of Transportation (NJDOT) also conducted several experiments on over-coating [34]. The most famous one was the experiments conducted

on Thomas Mathis bridge in the years 1986 and 1987 where the results were inspected in 2007, almost 20 years after the initial coating. The experimental systems consisted of inorganic and organic zinc coating, epoxies, aluminum poly urethanes, vinyls, urethanes, oil-alkyds, aluminum and zinc metalizing. These experiments show high probability of success with metalizing systems.

FHWA Reports

As per the reports of FHWA, out of 200,000 steel bridges in the united states 10 percent requires rehabilitation to prevent corrosion. Removing rust and repainting is a hard task and can cost up to 35 dollars per square foot. Over-coating can cost from 6 dollars to 10 dollars per square foot which is far economical than repainting [21]. Researchers at FHWA studied the performance of over-coating system through field exposure. The evaluation was done by measuring rust Creepage from X-shaped scratches made through the overcoat surface down to the steel substrate. Based on the results, the researchers concluded that coating thickness plays a critical role in development of surface rust. The results also indicate that there is no direct correlation between surface performance and scribe performance for overcoat systems [18,19].

Various technical bulletins published by FHWA describe the test methods used for evaluation of various commercial coating systems. It could be implied that these test procedures could be used for evaluating and accepting new coating systems. But these publications do not provide a clear acceptance criterion.

Summary

The basic mechanisms of coating degradation are: (i) creeping of corrosion from a coating-damaged location, (ii) surface layer degradation due to salt and Ultra Violet Rays (UV) radiation resulting the damage to prime layer and creation of corrosion spot, (iii) coating degradations at weld lines due to uneven thickness of coatings and accelerated corrosion due to change in metallurgy caused during the welding process, (iv) weak locations created by bolt holes and sharp edges and (v) abrasion caused by debris at deck joints and supports. In the case of overcoating, surface preparation plays an important role. Since surface preparations are expensive and time-consuming process, primers were developed to adhere to surfaces with less rigorous preparations. These primers were found to be ineffective in actual field applications [32]. Test methods have been developed to accelerate the aforementioned degradation mechanisms.

Corrosion creep was found to be the primary mechanism for deterioration of coatings. Oher mechanisms lead to creation of a rust spot and corrosion creeps from these locations. The current practice, well documented in ASTM specifications [8] and FHWA technical bulletins [18,19], is to artificially create an X-shaped scribe and measure the creep growth from the scribe. Salt solution, wetting and drying, UV exposure and heating are added to accelerate the corrosion growth. The corrosion growth, even under accelerated test conditions is limited to very small fraction of an inch and are difficult to measure because of the fussy growth.

Research done by the automobile industry identified a method to further accelerate the creep growth [30]. In this test, the researchers found that deep-freezing and thawing cycles could increase the creep growth by an order of magnitude, Figure 4. Difference in coefficient of thermal expansion of coating formulations and the metal are found to be primary cause for this accelerated creep growth.

Overcoating is an effective way to maintain steel structures. The cost of re-coating could be as much as 10 times the cost of spot-overcoating. In addition, damage caused by corrosion at critical locations such as supports, even though the rest of the span is good condition, can lead to catastrophic failure of the structure.

Clear and well-defined procedures for accepting new coating systems are not identified in the published literature. The report by US Army Corps of Engineers provides guidelines for choosing products for over-coat [44]. The agencies have to choose their own protocol using the existing test methods. A clear consensus on a well-defined protocol for acceptance is needed for adoption by the DOTs.

Information on performance of coatings under field conditions is very limited. Only one study carried out by NJDOT provides information over a 20-year period [34]. A few more studies are available, but the exposure duration is less than 5 years. The shorter exposure period can be used only to weed out very weak systems.

Since results on field exposure study are limited, very little research has been done on the correlation of laboratory and field performance. The fundamental weakness of the current status is that the tests do not provide the estimate of service life in actual field conditions. The tests are intended only for comparative evaluations. A successful test should correlate with actual field exposure for predicting all modes of failure.
Surface preparation is an important variable that impacts both cost and environment. Various levels surface preparation that are currently used are presented at the end of this section.

Zinc primers seems to provide the best performance. Both organic and inorganic version of zinc primers are available in the market and more and more DOTs are specifying the coatings with these primers. Currently, coating systems that can last for 100 years is not available [18,22].

Surface Preparation for Over-Coating Systems

Surface preparation is an important part of coating. This aspect becomes even more important for overcoating. Therefore, various levels of surface preparation and the details are presented in the following section.

Classification of Surface Preparation/Cleaning Procedures

Cleaning of the existing coating and the debris including the rust is an important part of over-coating. Therefore, various cleaning procedures commonly used are summarized in this section. The Society for Protective coatings (SSPC) defines the different levels of cleaning using the notation SP1 to SP15 presented in Table 2. These cleaning

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procedures are described briefly in the following sections.

Table 2 - Surface Preparation: Designation and Description

Designation	Description
SSPC-SP1	Solvent Cleaning
SSPC-SP2	Hand tool Cleaning
SSPC-SP3	Power tool Cleaning
SSPC-SP5	White metal blast cleaning
SSPC-SP6	Commercial blast cleaning
SSPC-SP7	Brush-off blast cleaning
SSPC-SP8	Pickling
SSPC-SP10	Near white blast cleaning
SSPC-SP11	Power tool cleaning to bare metal
SSPC-SP12	Cleaning of metals by water-jetting
SSPC-SP14	Industrial blast cleaning
SSPC-SP15	Commercial grade power tool cleaning

SSPC-SP 1 Solvent or Chemical Cleaning
This method involves the removal of dirt, oil, grease, soil, drawings, cutting compounds and other soluble contaminants with organic solvents, commercial cleaners, detergents. Wiping, dipping, steam cleaning or vapor degreasing could be part of the cleaning process.

Typical cleaning steps are:
- Wipe with rags or bushes that are wetted with solvent or
- Sprayed the surface with the solvent or
- Immerse completely in a tank of solvents.
- Clean with fresh rugs.
- Steam cleaning can also be used to remove the residues.

SSPC-SP 2 Hand Tool Cleaning
It is the method of preparing the steel surfaces with the use of non-power hand tools. It is acceptable method of surface preparation for normal atmospheric exposures, for interiors and for maintenance paint when using paint with good wetting abilities. The hand tool cleaning removes all the loose rust, loose mill scale, loose paint and other detrimental foreign matter. After cleaning, the surface should be brushed, dusted, swept and blown off with compressed air to remove all loose matter.

SSPC SP-3 Power Tool Cleaning
In this method, power tools such as brushes or power sanders, sanding disc, power chipping hammers, abrasive grinding wheels, needle guns are used to remove the rust and other debris. Power tooling is more effective and less laborious that hand tool

cleaning. The use of power assisted hand tools for the removal of loose rust, loose millscale and loose paint after removal oil and grease as specified in SSPC-SP1 is known a power tool cleaning. This method is not considered adequate for use under severe exposure or long-term exposure conditions. Care should be taken to prevent polishing of the metal surface. After power tool cleaning and before to painting, remove dirt, dust or similar contaminants for the surface. Acceptable methods include brushing, blow off with clean dry air and vacuum cleaning.

SSPC -SP5 White Metal Blast Cleaning

In this method, compressed air nozzle blasting, centrifugal wheels and/or other suitable methods are used for cleaning. Before blast cleaning, visible oil and grease should be removed using the specification of SSPC-SP1. The surface shall be roughened to a suitable degree for the specified coating system.

SSPC-SP 6 Commercial Blast Cleaning

This method is similar to SP 5 but done at a larger scale.

SSPC-SP 7 Brush Off Blast Cleaning

A brush off cleaned surface when viewed without magnification shall be free from all visible oil, grease, dirt, dust, loose mill scale, loose rust and loose coating. Tightly adherent mill scale, rust and paint may remain on the surface. Brush blast cleaning should be used when the service environment is mild enough to permit tight mill scale, coating, rust and other foreign matter to remain on the surface. The methods and operations for brush off blast cleaning is same as white metal blast cleaning.

SSPC-SP 8 Pickling

The method of preparing the steel surfaces with chemical reaction or electrolysis in acid solutions is referred to as pickling. The surface when viewed without magnification shall be free of all visible mill scale and rust. The degree of cleanliness is similar to white metal blasting.

SSPC-SP 10 Near White Metal Blast Cleaning

The removal of all visible oil, grease, dirt, dust, millscale, rust, paint, oxides and other foreign matters by compressed air nozzle blasting, centrifugal wheels or other specified methods. Random staining should be limited to no more than 5% of each unit area of the surface. The surface may not be completely free of light shadows, slight streaks or minor discolorations caused by stains of rusts and millscale, or stains of previously applied coating. Before blast cleaning visible oil and grease should be removed using the specification of SSPC-SP1.The blast cleaning abrasive should be dry and free of oil, grease and other contaminants. The cleaning method and operations are similar to that of white metal blast cleaning. It should be used when high degree of cleaning is required.

SSPC-SP 11 Power Tool Cleaning to Bare Metal

This standard is suitable where a roughened, clean, bare metal surface is required but where abrasive blasting is not feasible or permissible. Metallic surfaces which are prepared according to this specification when viewed without magnification, shall be free of all visible oil, grease, dust, mill scale, rust, paint, oxide, corrosion products and other foreign matters. Slight residues of rust and paint may be left in the lower portion of pits if the original surface is pitted. Remove all the visible deposits using SSPC-SP 1. All the sharp edges, sharp fins, weld spatters and other surface imperfections should be removed prior to power tool surface preparations.

SSPC-SP 12 Waterjetting

Surface preparation and cleaning of steel and other hard metals is achieved by high and ultra-high-pressure water jetting. In this standard there is no addition of solid particles to the stream. Water discharged from a nozzle at a pressure higher than 70MPa(10,000psi) is used to prepare the surface. The velocity of water often exceeds 340m/s(1,100ft/s) when exiting the orifice. The deposits of oil, grease and other foreign matters should be removed by water cleaning or steam cleaning methods of SSPC-SP1. The four-surface cleanliness in terms of visual contaminants are as follows.

- WJ-1: Clean to bare substrate
- WJ-2: Very thorough or substantial cleaning
- WJ-3: Thorough cleaning
- WJ-4: Light cleaning

SSPC- SP 14 Industrial Blast Cleaning

An industrial blast cleaned surface when viewed without magnification shall be free from all visible oil, grease, dust and dirt. Traces of tightly adherent millscale, rust and coating residues are permitted to remain on 10% of each unit area of surface. Shadows, streaks, discolorations caused by stains of rust of the previously applied coating may remain on the surface. The cleanliness methods and operations are similar to that of white method blast cleaning.

SSPC-SP 15 Commercial Grade Power Tool Cleaning

Power tool cleaning should be used to produce a bare metal surface. Remove all visible oil, grease, dirt, mill scale, rust, paint, oxide, corrosion products, and other foreign material. Random staining is allowed provided it is limited to no more than 33% per unit area of surface. A surface profile of 1 mil (25μ) shall be produced. Slight residues of rust and paint may be left at the bottom of the pits if the original surface is pitted. Before blast cleaning visible oil and grease has to be removed as discussed under SSPC-SP1. Before blast cleaning surface imperfections such as sharp edges, fins, weld spatter shall be removed from the surface.

The following are the comparative features of the various cleaning levels:
- White metal blasting(SSPC-SP5) provides a greater degree of cleaning than near white metal blasting(SSPC-SP6).

- The difference between white metal blasting and a near white metal blasting is that white metal blast removes all the coating, rust, millscale and other foreign matters from the surface. Whereas near white blasting allows light shadows, slight streaks, minor discolorations caused by stains of rust, millscale and previously applied coating to remain on no more than 5% of each unit area of the surface.
- Commercial blast cleaning (SSPC-SP6) provides a greater degree of cleaning than industrial blast cleaning(SSPC-SP14), but less than near white blast cleaning(SSPC-SP10).
- The difference between the commercial blast and a white near blast is the amount of staining permitted to remain on the surface. Commercial blast allows stains and shadows on 33 % of each unit area of surface. Near white blast allows staining or shadows on only 5 % of each unit area.
- Brush off cleaning (SSPC-SP7) provide a lesser degree of cleaning than industrial blast cleaning(SSPC-SP14).
- The objective of brush off blast cleaning is to retain as much of an existing coating as possible and to roughen the surface prior to coating application. But the purpose of industrial blast is to remove most of the coating, millscale and rust.
- Near white blasting provide a greater degree of cleaning than commercial blast cleaning but less than white metal blast cleaning.
- The difference between near white blast(SSPC-SP10) and commercial blast (SSPC-SP6) is that commercial blast allows staining on 33% of each unit area of the surface, whereas near white blast allows staining on only 5% of each unit area of the surface.
- Power tool cleaning to bare metals(SSPC-SP11) produces a greater degree of cleaning as compared to power tool cleaning(SSPC-SP3). Power tool cleaning requires only the removal of loosely adherent materials and does not require producing or retaining a surface profile.
- Industrial blast cleaning (SSPC-SP14) provides a greater degree of cleaning than brush off cleaning(SSPC-SP7) but less than commercial blast cleaning(SSPC-SP6).
- Commercial grade power tool cleaning (SSPC-SP15) differs from power tool cleaning(SSPC-SP3), in that a high degree of surface cleanliness is required and a minimum surface profile of 25 micrometers will be retained or produced. Commercial grade power tool(SSPC-SP15) also differs from power tool cleaning to bare metal(SSPC-SP11), in that stains of rust, paint, or millscale may remain on the surface.

- Waterjetting may be effective in removing water soluble surface contaminants that may not be removed by dry abrasive blasting alone. Waterjetting is used in areas where abrasive blasting is not the feasible method of surface preparations.

Quality Assurance

The research team surveyed similar work done by other state DOTs using the IR scan technology. The data collected showed that many states use the qualitative approach of IR scans as acceptance criteria. The literature search revealed that no state has implemented IR scan quantitative criteria for their quality control of steel paints. The New Jersey Department of Transportation currently uses a quality standard correlation of 0.98 or higher for all steel paints. Although this may seem like a fairly high and relatively safe correlation to abide by, every paint possesses their own unique chemical and physical properties and may not have the same acceptable correlation values. The NJDOT is seeking a more accurate quality testing standard system. The purpose of this research is to interpret IR scans of structural steel paints and then establish a unique correlation for each paint based on a large sample of scans. The ultimate goal is to establish acceptability criteria and determine acceptable tolerances for job samples compared to manufacturer samples.

SUMMARY OF THE WORK PERFORMED

In this section, the work performed to evaluate the proposed test method is described. This section covers two major topics. A new protocol for evaluating the durability of coatings used for reducing corrosion of steel structures which deals with the procedure for accepting new coating systems, is described in the first section. The work on quality assurance are presented in the next section.

Summary of the New Protocol

A new protocol for evaluating durability of coatings and their effectiveness in reducing corrosion of steel structures is presented in this paper. The major difference between the proposed method and the current practice is the way the corrosion creep from a coating-damaged location is measured after exposure to accelerated corrosive conditions. The proposed method is based on direct pull-off (adhesion) strength at various stages of corrosion. These pull-off strengths provide quantitative and repeatable measurements for quantifying the degradation. In the area of accelerated exposure conditions, deep freezing is incorporated as part of the accelerated degradation process. These two measures provide "significant and clearly measurable degradation" within three months of accelerated exposure. Coatings that are known to provide excellent and weak corrosion protection were tested using the proposed protocol and the results show a clear difference between the best and the poor coatings. The test results are also compared with one of the long-term field study. The focus of the experimental investigation was on transportation structures because of their vulnerability to corrosion due to the use of salts for improving driving conditions during the winter weather.

The corrosion of coated (painted) metal structures is influenced by a number of factors, including: corrosive atmospheres, rain, condensed dew, UV light, wet/dry and freeze/thaw cycling, and extreme temperature variations. The transportation structures are exposed to additional chemicals used for melting snow. All these factors frequently have a synergistic effect on one another, ASTM [8]. Extensive worldwide research has been conducted both for developing coatings (paints) to reduce corrosion and test methods to evaluate the effectiveness of these coatings. Transportation agencies in the United States of America (USA), both at federal and state level have sponsored a large number of studies over the decades. The objective was to identify coatings that will last for at least 25 years and preferably 100 years. In addition, these coatings should be conducive for field applications and the cost should be reasonable. Some of the latest publications dealing with durability of coatings concluded that current coatings cannot provide protection for 100 years [18,22]. Another challenge is to develop accelerated test methods to predict the long-term behavior of the coatings under field conditions. The key issues are: linking laboratory performance under accelerated corrosion to field performance, identifying exposure conditions to induce corrosion in a reasonable amount of time, procedures to measure and quantify the response variables such as corrosion growth at damaged locations, deterioration of the coating material and a model to link the laboratory performance to field performance. The owners of the structures including Department of Transportation and other public/private agencies

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such as Port Authorities and Railroad corporations are in need of a test protocol for accepting new coatings. If the test methods are time consuming and very expensive, the new innovative products developed by companies with limited resources will not make it to the market. Therefore, the test methods should be effective but at the same time should not be cost prohibitive. The results presented in this report deals with a test method that can provide results within 6 months.

The exposure conditions for the proposed accelerated test was chosen based on the current best practices adopted in various ASTM standards and used by researchers in the fields of transportation, pipeline, energy and automobile industries. The corrosive chemicals were chosen to reflect the road-salts used by the Department of Transportation of New Jersey (NJDOT), USA. It is well established that the primary degradation mechanism for the coatings is progress of corrosion from an area where the coating is damaged. The current practice is to measure the growth of corrosion from an artificially created damage in the shape of X. The growth could be only a few millimeters (a small fraction of an inch) even after considerable exposure and measuring this growth accurately is also very difficult. It is proposed to use a more robust method which is easy to use and provides easily quantifiable measurement of corrosion progress from a (coating) damaged location. The degradation of the coating itself is evaluated using change in thickness of the coating, change in color and visual inspection. Using the proposed method, tests were conducted for 6 commercially available NJDOT approved coatings. The results show a clear difference between the strong and weak coatings that are currently being used for bridges. The results also correlate well with the 20-year field performance study conducted by NJDOT [34].

Key aspects of the proposed test protocol

The following are the key parameters of the proposed accelerated test.
- Selection of test specimens and specimen preparation
- Exposures conditions and duration of various cycles
- Response variables and their measurement
- Criteria for acceptance of the coating.

The test samples made of rolled steel angle sections were chosen to represent the structural components used in transportation infrastructure. A line of weld was placed on the samples because welded surface is more prone to corrosion. In addition, bolt holes were drilled to simulate field conditions.

Exposure conditions were chosen using the current ASTM standards. Accelerated corrosion is induced by exposing samples to wetting and drying of salt solutions and UV radiation. One major addition was exposing the samples to deep freezing for 8 hours based on a study conducted for automobile structures [30]. Exposure to deep freezing accelerates the growth of corrosion from a damaged location.

The dominant response variable is corrosion growth from a location where the coating is damaged. To accelerate the corrosion more than the current practice, coating was

removed from to create an isolated circular coating. In this case the corrosion advances from the perimeter of the circle towards its center as compared to the current practice in which corrosion growth is measured from a single X cut. In addition, the level of corrosion growth is measured by obtaining direct tensile pull-out (adhesion) strength of the circular coating. As the corrosion progresses, the tensile pull-out load decreases providing an easily quantifiable response variable. To measure the deterioration of the coating material, change in thickness and color were also measured at various stages of accelerated exposure. In addition, visual inspection was conducted to assess the damages at weld and bolt-hole locations.

Acceptance criteria was developed using the laboratory and field performance of the best and worst performing coatings. Acceptable limits were identified for all the four response variables. The proposed duration of actual test is 100 days. The entire evaluation including the specimen preparation and analysis of results can be conducted in 4 to 6 months.

More details of the various components of the protocol including: equipment used, test procedure, analysis and interpretation of results, summary of a field study, comparison of laboratory and field study are presented in the following sections.

Selection and Preparation of Test Specimens
The test specimens consisted of 2-in by 2-in by 12-in (long) rolled-steel angles. The rolled steel specimens were chosen to simulate typical steel bridge components. Two ½ inch diameter holes were drilled thru one leg of the angle, and two 1-inch long welds were placed on the other leg (Figure 2 and 3). The line welds were placed because welding is known to increase corrosion in steel due to chemical changes caused by high temperature. The holes were drilled to simulate connections in the steel structural elements and to determine any possible pitting corrosion near the holes. In some sections bolts and nuts were also used. The smaller size samples were chosen for easy handling and to limit the size of the corrosion chamber.

The next step was surface preparation. To simulate the application of coatings to existing structures where deteriorated coating present on the surface should be removed, the surface was cleaned using hand operated power tools. The surface preparation of the steel angle was in conformance with the paint manufacturers requirements. Aurand hand held steel toothed cleaning machine was used in the current investigation. This step was followed by the application of the coating. To simulate the damage of the coating, a circular uncoated ring was created during the coating operation. It was found that creating this ring by placing O-rings was much more efficient than cutting a perfect circle after the coating was applied.

The following are the sequence of steps for creating circular ring of uncoated surface. In each face of the angle, five plastic O-rings were attached using a water-soluble glue (figure 3). The inner and outer diameters of the rings were 20.6-mm (0.81-in.) and 23.8-mm (0.94-in.), respectively. After the water-soluble glue has cured, the coating was applied using the manufacturer's specified procedure. These O-rings were removed after painting, to create an uncoated ring that is approximately 3-mm (0.12-in.) wide and

a coated 20-mm (0.79-in.) diameter circle. During the exposure to accelerated corrosion cycles, the corrosion creeped around the circular ring towards the center. The adhesive strength of the coating over the circle was used as the indicator of the corrosion creep. Direct pull-off test was conducted using an ASTM procedure at various stages of corrosion.

A low-pressure sprayer was found to be very effective for applying the coatings with uniform thickness. These sprayers can be used for Overcoating small areas in the actual field applications. The coating thicknesses were measured at a number of locations to ensure both the coating thickness and quality in terms of variation of thickness satisfied manufacturer's specifications. For multi-layer coatings, thickness of each coating was checked. After the coating layers have cured (as per manufacturer specification), the O-Rings were removed, leaving approximately a 3-mm wide exposed steel scribe around coated circles with 20-mm (0.79-in.) diameter. Any residue from the water-soluble glue was carefully removed with wet cloth. A typical coated specimen with the O-rings removed is shown in Fig. 3.

Figure 2. Specimen preparation: Location of typical ½-inch diameter holes and welds
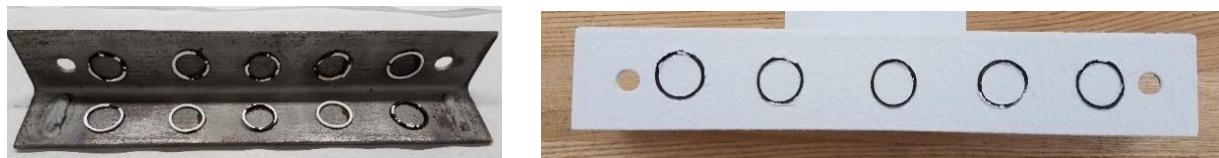
Figure 3. Specimen preparation: Attachment of O-rings using water soluble glue and their removal after the curing of the coating.

Exposures conditions and duration of various cycles

The exposure conditions for the accelerated corrosion were chosen based on:

- Science of corrosion
- Current test practices based on the state of the art
- Guidelines provided in ASTM, USDOT, Other state DOTs
- Army Corps of Engineers and
- Practices used in automobile, navel, pipeline and oil industries.

ASTM D5894-16 [7] was used as the basic standard for the exposure scheme. For wetting and drying cycles, instead of 4 hours specified in ASTM D5894-16 [7], 1-hour wetting period followed by a 1-hour drying period was used to further accelerate the

creep of corrosion. The wetting and drying periods were rotated one after another for 8 cycles each, over a 16-hour period in a day. The spray solution for wetting was prepared at a concentration of 5 percent salt by weight using the de-icing salts of NJDOT. Note that ASTM does allow the use of specific chemical formulations for a chosen application. During the drying period the specimens were also exposed to UV irradiation resulting in 8-hours of irradiation exposure per day, as compared to 4 hours UV exposure specified in ASTM D5894-16 [7]. After these 8 cycles of wetting and drying each, the specimens were placed for deep freezing for remaining 8 hours. Exposure to very low temperature was shown to accelerate the creep growth [30] as shown in Figure 4. The combined exposures on a single day was designated as 1 master cycle. The cycle starts in the morning with exposure to heat and UV radiation. The samples are placed in the freezer at the end of the day. Wetting/drying and exposure to UV radiation cycles were automated and the samples were placed in the freezer manually. The salt solution was replaced after every master-cycle.

(a)   (b)
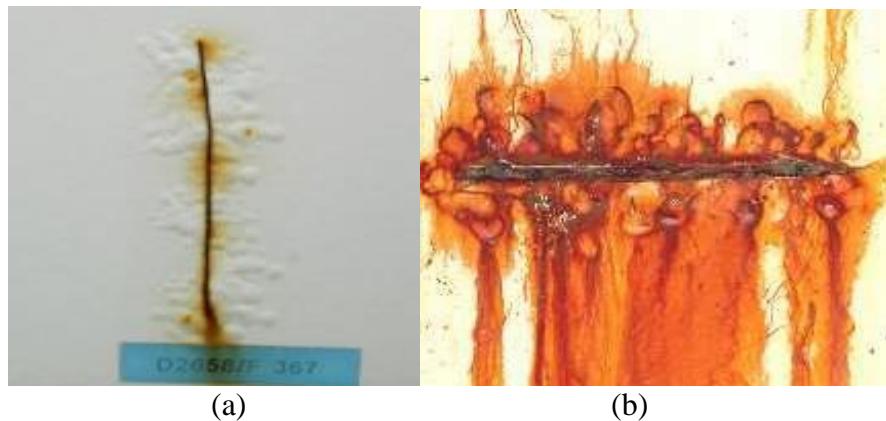
Figure 4. Creep growth at scribe: (a) without deep freeze cycles and;
(b) with deep freeze cycles [30]

Details of Accelerated Test Chamber and Freezer

A test chamber was designed and fabricated using the information available in the literature with particular emphasis on ASTM standards, Figure 5. The key parameters were: exposure to salt spray and UV radiation. A salt spray was chosen for the current system instead of fog specified in ASTM D5894-16 [7]. The motivation for this decision was to better simulate rain and water-run off exposure that occurs with existing structures. Fog spray does not simulate these typical conditions. Salt solution used in the current system was prepared by dissolving salt used by NJ DOT at a concentration of 5% by weight. The sodium chloride content in the salt simulates typical roadway de-icing salt used by department of transportations.

The chamber used for accelerated corrosion consisted of a plastic tank that does not corrode. Metal tanks that do not corrode can also be used instead of plastic tank. A holding rack for placing specimens was built inside the tank using the guidelines of ASTM D5894-16 [7] and ASTM B117-16 [4]. The holding rack built using a non-

corrosive/conductive material, supports specimens at an angle between 15° and 30° from the vertical axis. These racks were placed parallel to the principal direction of the salt spray in the chamber.

Figure 5. Chamber for Accelerate Testing: Salt Sprayers and Holding Rack

Ultraviolet irradiation was also included in new system following the guidelines of ASTM D5894-16 [7] and ASTM G154-16 [3]. The type and placement of UV light bulbs were also done using ASTM guidelines. However, instead of using a separate UV/condensation cabinet, UV light source was made as a part of the main chamber. The irradiation exposure was combined with drying cycle resulting in 8 hours UV radiation for each master cycle.

For the deep freeze exposure, a commercially available deep-freezer was chosen. This freezer provided a temperature of -20 ± 5°F (-29 ± 3°C) satisfying the guidelines in ASTM D6944-15 [9]. Similarly, to provide an accelerated thawing environment in the chamber, a heating system capable of achieving and maintaining a temperature of 122 ± 5°F (50 ± 3°C) within an hour was installed, following ASTM D6944-15 [9] guidelines. The accelerated heating system also provided the needed drying system, as compared to ASTM D5894 [7] in which the drying is done using compressed air. The operation of salt sprayers, UV lights and heating system was automated using timers. Movement of specimens to and from deep freezer and replenishment of the salt solution every day (one master cycle) was done manually.

Response Variables

Pull-off Test

The pull-off test was used to determine adhesion strength and its correlation to corrosion growth around the perimeter of the pre-placed circular scribe to the coating. The tests were conducted using the specification of ASTM D4541-17 [5], Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers. Adhesion

strength of the 20 mm diameter coatings isolated by the scribe, Figure 6, were measured at various stages of corrosion. The first set of adhesion strengths were obtained after proper curing of the coatings. For these tests, a minimum of three 20 millimeter pull off dollies were adhered to the circular painted areas within the scribe using a two-part manufacturer supplied epoxy, Figure 6. The epoxy was cured for a minimum of 24 hours. The pull off tester used was PosiTest® AT-M Manual Adhesion Tester, Figure 7 and 8. The tensile load was applied at a constant rate of 150 psi/s (1 MPa/s). This rate of loading was chosen to satisfy the requirement that the test has to be completed within 100 seconds. After each test, the maximum tensile stress and failure mode were recorded. The pull off dollies were then labeled and kept for comparative evaluation at various stages of corrosion. Once testing was completed, the specimens were placed in the test-chamber for accelerated testing. Pull-off tests were conducted for virgin samples and at intervals of 14 master cycles. Final tests were conducted after 100 master cycles of exposure.

Figure 6. Pull Off Dolly (20 millimeter): Epoxied to Over Coated Steel Specimen

Figure 7. Pull Off Tester and 20 millimeter Pull Off Dollies
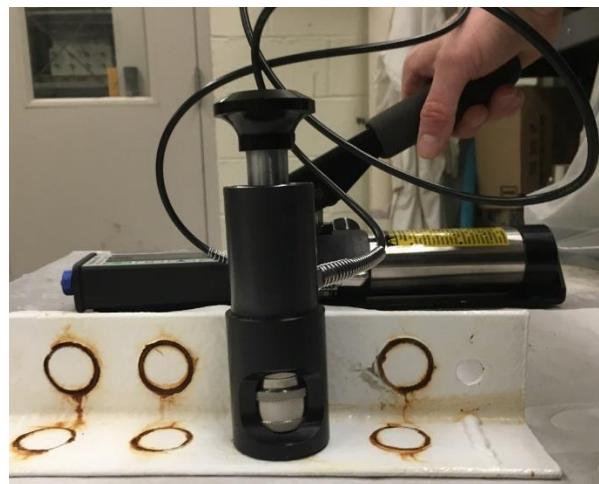
Figure 8. Pull-off test in progress

After each 14 master cycles of exposure in the accelerated corrosion chamber, the specimens were taken out, rinsed with clean water to remove any debris or residue and dried with low-pressure compressed air. After cleaning, three 20-mm pull off dollies were adhered to the circular painted areas within the scribe using a two-part manufacturer supplied epoxy and cured for the required minimum of 24 hours. After the epoxy was cured, adhesion strengths were measured. The test in progress and the sample before and after pull-off are presented in Figures 8 and 9, respectively. Images of corrosion growth for the best and worst coating system evaluated in the current investigation are presented in Figures 10 and 11. These images were taken after the 20 mm diameter circular coating was pulled-off during the pull-off tests.

Figure 9. Images of circular coating: Before and after pull off test
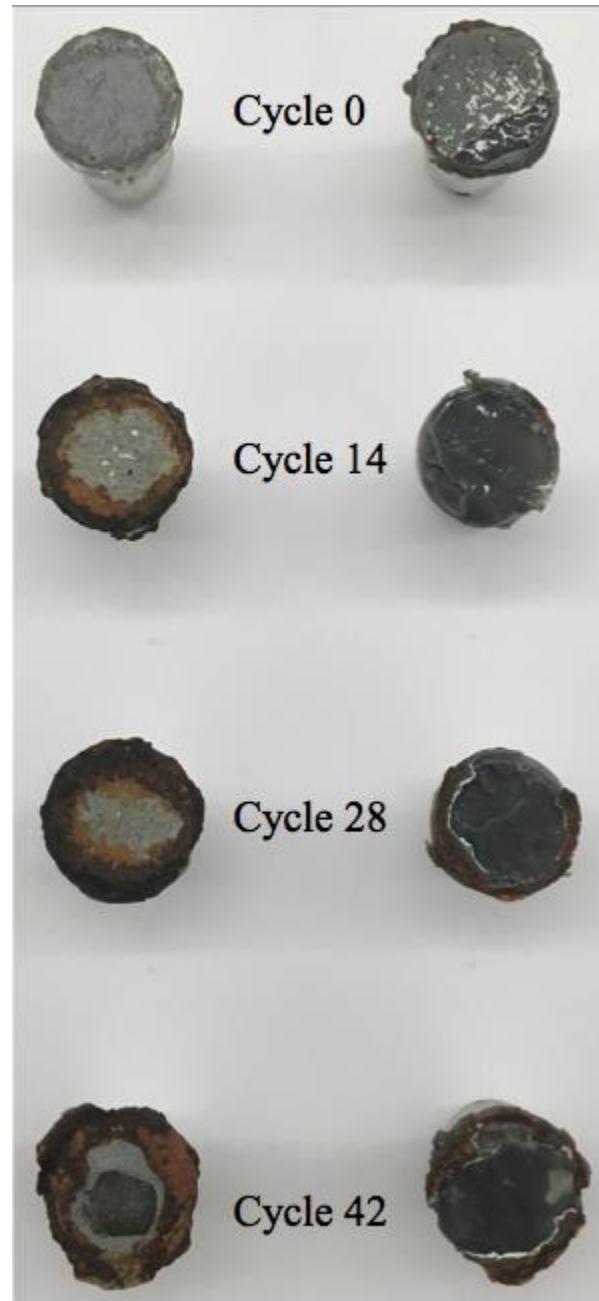
Figure 10. Worst and Best Performing Coating System: Images of corrosion growth after circular coatings were pulled-off, Cycle 0 to 42
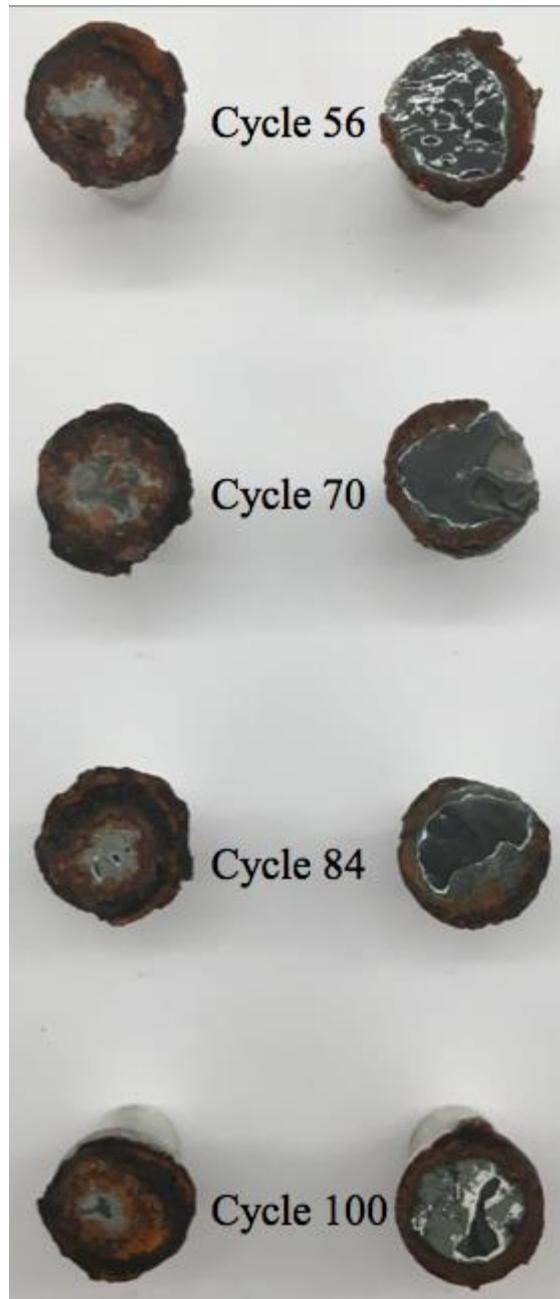
Figure 11. Worst and Best Performing Coating System: Images of corrosion growth after circular coatings were pulled-off, Cycle 56 to 100

*Interpretation of Pull Off Test results*

The pull off strengths obtained at various stages of corrosion were used to estimate the corrosion-creep growth. Assuming the adhesion strength of coatings at un-corroded areas are same as the initial strength, average area of un-corroded coating was calculated. As the pull off strength decreases as result of reduction in contact area, it is assumed that the pull off strength determined from the virgin sample is retained in the un-corroded areas. Therefore, the un-corroded area can be converted to the radius of a circle that is not corroded. Hence the average corrosion creep can be estimated by subtracting this radius from the original radius, which is the radius of scribe (10 millimeter). Note that for this computation, the corrosion around the perimeter is assumed to be uniform. The following are the steps of a typical calculation:

- Pull-off strength for the virgin sample = 800 psi or 400 lb. (area of 20 mm dia. circle is 0.5 Sq. inch)
- Pull-off strength at a given exposure, 400 psi or 200 lb.
- Assuming the original adhesive strength is same in un-corroded areas, un-corroded area = 200/ 800 Sq. inch.
- Radius of un-corroded area = $(200/ \{800 \times 3.14\})^{1/2}$ = 0.28 in or 7.2 mm
- Corrosion Creep = original radius of 10 mm- radius after corrosion
- Corrosion Creep = 10- 7.2 = 2.8 mm

Note that the computed corrosion creep represents an average of the corrosion growth of around 20 mm diameter circle towards the center and therefore can be used only for comparative purposes.

Color Change

Visual inspection along with a device called Colormeter, Figure 12, were employed to monitor the color change of the coatings during the testing. The Colormeter provides three readings designated as a*, b*, and L* coordinates. These coordinate numbers change with the change in the color of the coatings and provide a quantitative measure of the color changes. Since the color change is gradual and not significant, the measurements were made only at the beginning and the end of the exposure period, representing 0 and 100 cycles. Readings were taken at 9 random locations and the average was obtained. For the samples exposed to weathering, the surface was cleaned to remove the rust spots before taking the Colormeter readings.

Figure 12. Konica Minolta CR-10 Plus Color Reader

Thickness Change

Change in thicknesses of the coatings during the weathering cycle exposure were monitored using a thickness measuring gage, Figure 13. A minimum of three readings were taken to obtain an average thickness.   Again, as the change in thickness was not significant, measurements were made only at 0 and 100 cycles. As in the case of color change measurement, readings were taken at 9 random locations and the average was obtained.

Figure 13. Thickness gage used for measuring the thickness of paint layers

Visual Inspection

Visual inspection was also used to determine any significant changes in color, peeling of coatings or any other anomalies. Particular emphasis was given to the locations of bolt holes and welds.

Selection of Coating systems for Evaluation

The proposed protocol was evaluated using six commercially available coating systems. These coating systems are currently approved by NJDOT for Overcoating applications. Based on the information available in the published literature and the field evaluation conducted by NJDOT, three of these coatings were judged to be very weak, one was judged to be weak and two others were judged to be the best performers. For the first layer; the 3 very weak systems had mastic, the 4th system had an Alkalyd, 5th system had organic zinc and the 6th system had inorganic zinc. It was envisioned that; the first layer will be the key contributing factor for the coating deterioration. The results of this investigation confirm this hypothesis. Details of these coating systems are presented in Table 3. The complete list of coating systems approved by NJDOT as of 2017 are presented in Table 4.

Table 3 - Details of Over Coating Systems Used in the Investigation

Coating System Designation	Primer Layer	Intermediate Layer	Top Layer
1	Phenalkamine Epoxy	N/A	Aliphatic Acrylic-Polyester Polyurethane
2	Polyamine Bisphenol A Epoxy	N/A	Acrylic Polyurethane
3	Carbomastic Epoxy	N/A	Aliphatic Acrylic-Polyester Polyurethane
4	Epoxy (Alkalyd)	N/A	Aliphatic Urethane
5	Polyamide Epoxy - Organic Zinc Rich	Polyamide Epoxy	Aliphatic Acrylic Polyurethane
6	Solvent Based Inorganic Zinc	Cycloaliphatic Amine Epoxy	Aliphatic Acrylic-Polyester Polyurethane

Table 4 - NJDOT-approved list of Epoxy Mastic Paint Systems as of 2018 (Reproduced verbatim from NJDOT Documents)

Selected Database:	QPL_APPROVED_MATERIALS.DB	
Material Name:	PAINTS, EPOXY MASTIC SYSTEM	
Specification Reference:	912.01	
Date/Time:	Monday, February 23, 2015 at 11:18:06	
Product Name	**Manufacturer/Supplier**	**General Comments**
EU-09 CARBOLINE SYSTEM	CARBOLINE CO. - ST. LOUIS, MI	CARBOMASTIC 90 CARBOTHANE 134 HS
EU-16 INTERNATIONAL PAINT SYSTEM	INTERNATIONAL PAINT - HOUSTON, TX	PRIMER - INTERPLUS 356 TOPCOAT - INTERTHANE 870 UHS
EU-04 INTERNATIONAL PAINT SYSTEM	INTERNATIONAL PAINT - HOUSTON, TX	BAR-RUST 235 DEVTHANE 359
EU-10 MAB SYSTEM	MAB - MALVERN, PA	PLY-MASTIC 101 PLY-THANE 870 HS
EU-12 PPG / AMERON SYSTEM	PPG / AMERON PROTECTIVE AND MARINE COATINGS	AMERLOCK 2 AL AMERCOAT 450 H
EU-13 SHERWIN WILLIAMS SYSTEM	SHERWIN WILLIAMS CO. - MALVERN, PA	EPOXY MASTIC ALUMINUM HIGH SOLIDS POLYURETHANE B65 SERIES

Tests were conducted using a minimum of 3 samples for each coating system. In addition, the entire test was repeated for one of the coating system to verify the repeatability of the test. The procedure outlined in the aforementioned sections were followed for all the tests. Pictures of test sample and use of measuring equipment for adhesion strength are shown in Figures 14 to 16. The typical pull-off test for a corroded sample is shown in Figure 14, in which the corrosion progress around the circular perimeter can be seen. Elevation and plan views of a typical dolly attached to the coating using epoxy are shown in Figures 15 and 16, respectively.
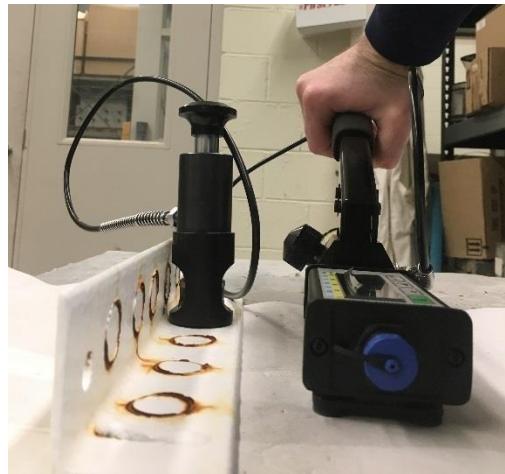
Figure 14. Typical Pull Test

Figure 15. Pull Off Dolly (20 Millimeter): Epoxied to Inorganic Zinc Over Coated Steel
Specimen

Figure 16. Pull Off Dolly (20 Millimeter): Epoxied to Epoxy Mastic Over Coated Steel Specimen

Results and Discussion

The response variables were: loss of adhesion strength of the coating due to corrosion creep, color and thickness change, and changes observed during the visual inspection. Visual inspection was used for determining the effect of welds and bolt-holes. As expected, progression of corrosion from a damaged location was a major contributing factor for the deterioration of the coatings. Adhesion strength, measured using a direct tension pull-off test provided a clear measurable indicator for the durability of the coatings. Pull-off strengths were used to estimate average corrosion-creep growth. Both the pull-off strengths and creep growth are presented in the following sections.

A careful evaluation of the experimental results leads to the following over-arching observations:

- Progress of corrosion from a location with damaged or weak coating is not only the primary contributor to degradation of the coatings but also this deterioration mechanism occurs much more rapidly as compared to other modes of deterioration such as degradation of the coating itself or effects created by welding or bolt-holes. Welding and other type of connections do initiate corrosion because these locations are prone to weak or non-uniform coating that develop into a damaged location. However, artificially inducing a damage is the most efficient way to accelerate the corrosion and therefore almost all the test methods specify this mechanism for evaluating coatings. The results of this investigation concur with the existing hypothesis.

- The unique characteristics of the proposed method are use of a circular scribe to magnify deterioration growth resulting much more rapid deterioration as compared to the currently X scribe and quantitatively measurable response variable, namely adhesion strength. The circular scribe not only enhances the

accelerated corrosion but also provides viable geometry for measuring adhesion strength.
- Since the growth of corrosion from the damaged location was very rapid, significant changes did not occur due to other possible deterioration mechanisms such as change in thickness or fading of color.
- Corrosion growth with respect to number of cycles occurs at a rapid rate in the beginning. For some coatings the rapid growth also occurs at later stages.
- In the opinion of the authors, exposure to 100 master cycles over a period of 100 days, will be sufficient to create measurable damage for any type of coating. Therefore, a new coating system can be evaluated within a period of 6 months using an economical test set-up.
- When more results on field behavior becomes available a correlation could be developed between the accelerated test results and actual field performance.

The results for the various coating systems are presented and discussed in detail in the following sections.

Adhesion Strength Measured using Pull- off Tests
The results of the pull off tests are presented in Figures 17 to 22. Direct pull-off strength versus master cycles are presented for five coating systems and the replicate test of Coating 1. Note that 1 master cycle consist of: 8 cycles of wetting, 8 cycles of drying, 8 hours of UV exposure during the drying cycles and 8 hours of deep-freezing.
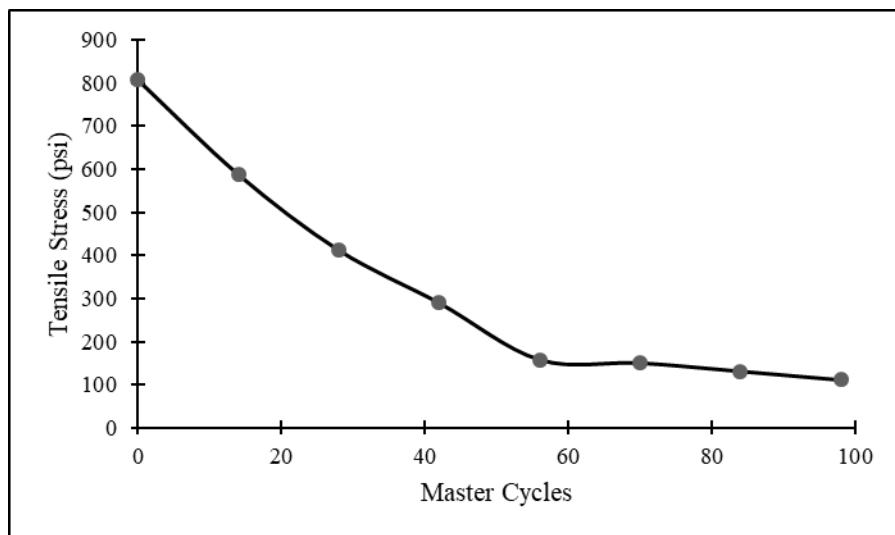
Figure 17. Direct Tensile Stress versus Number of Cycles: Coating 1
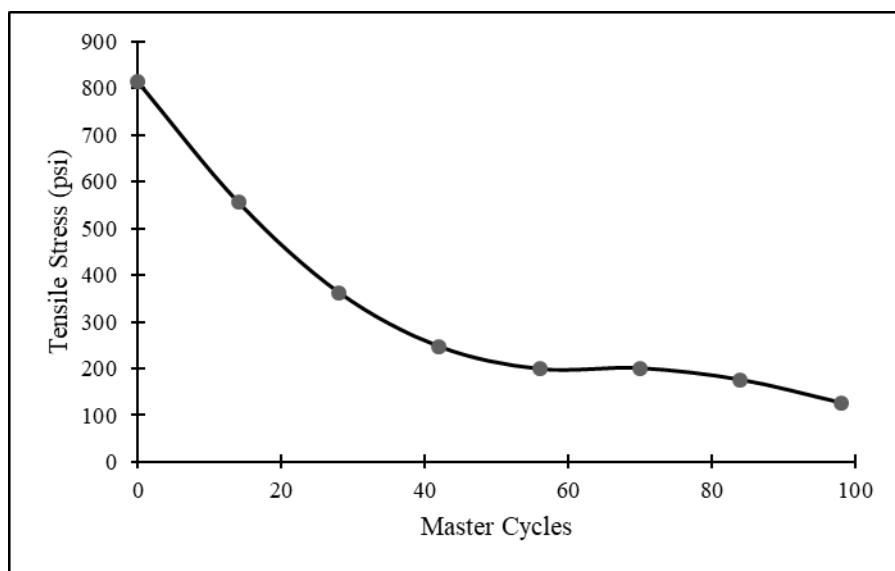
Figure 18. Direct Tensile Stress versus Number of Cycles: Coating 2
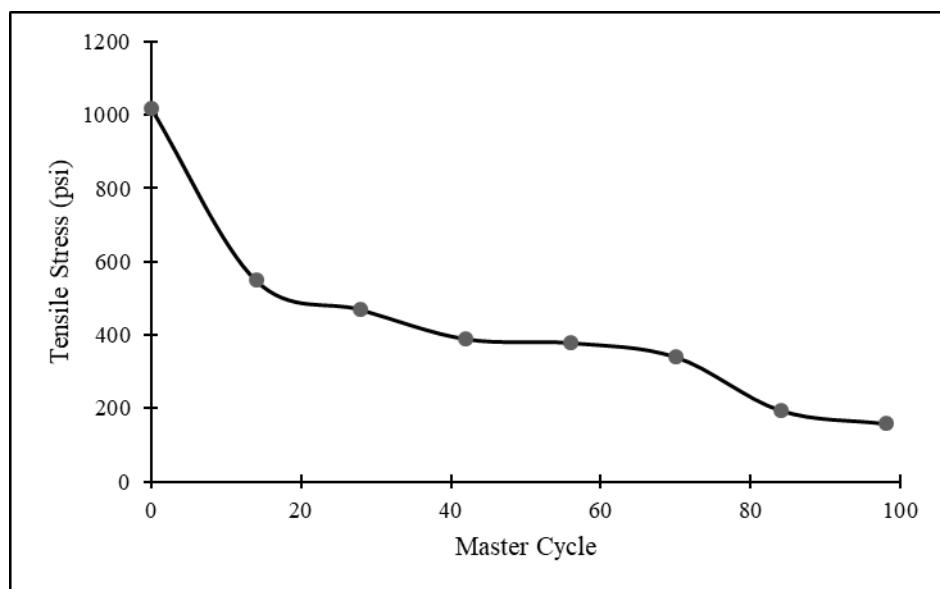
Figure 19. Direct Tensile Stress versus Number of Cycles: Coating 3
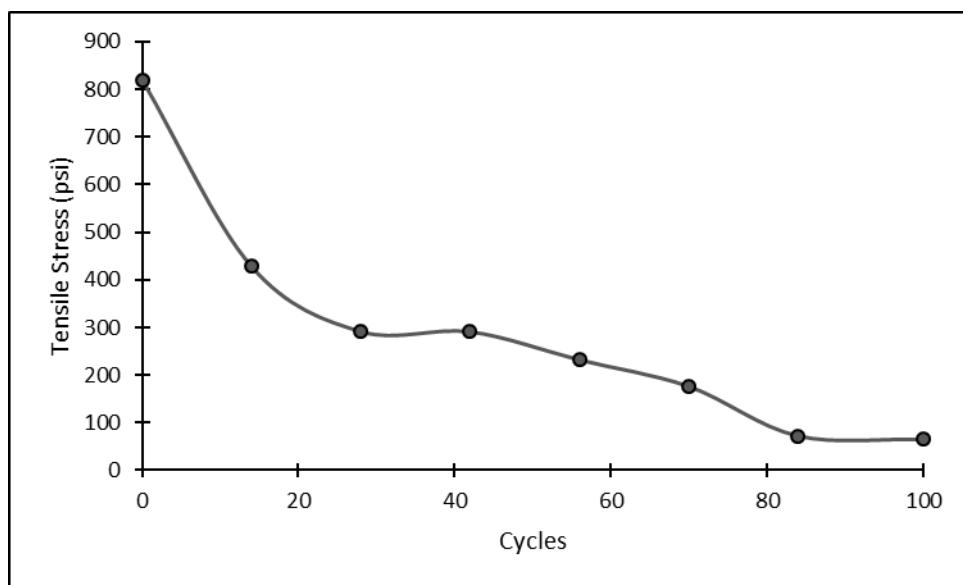
Figure 20. Direct Tensile Stress versus Number of Cycles: Coating 4
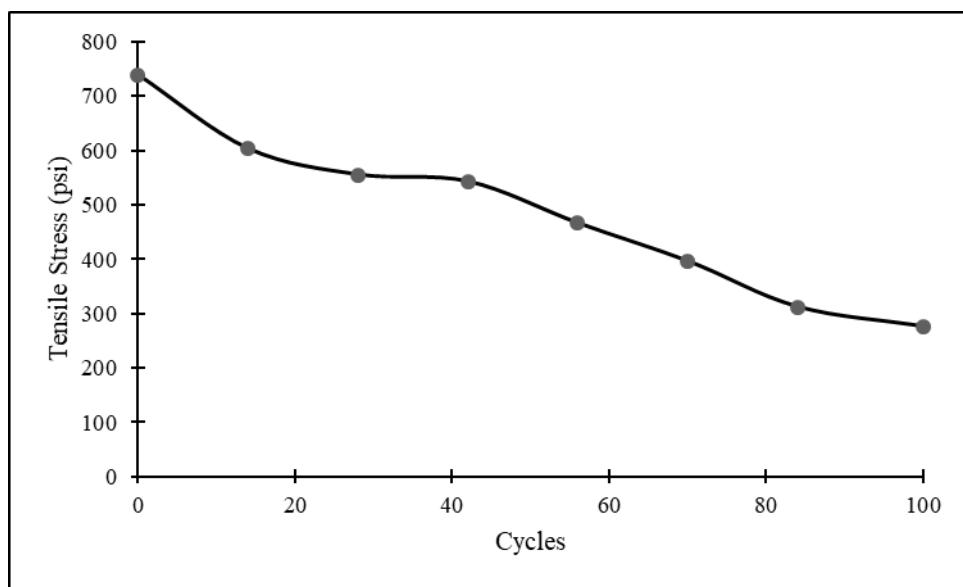
Figure 21. Direct Tensile Stress versus Number of Cycles: Coating 5
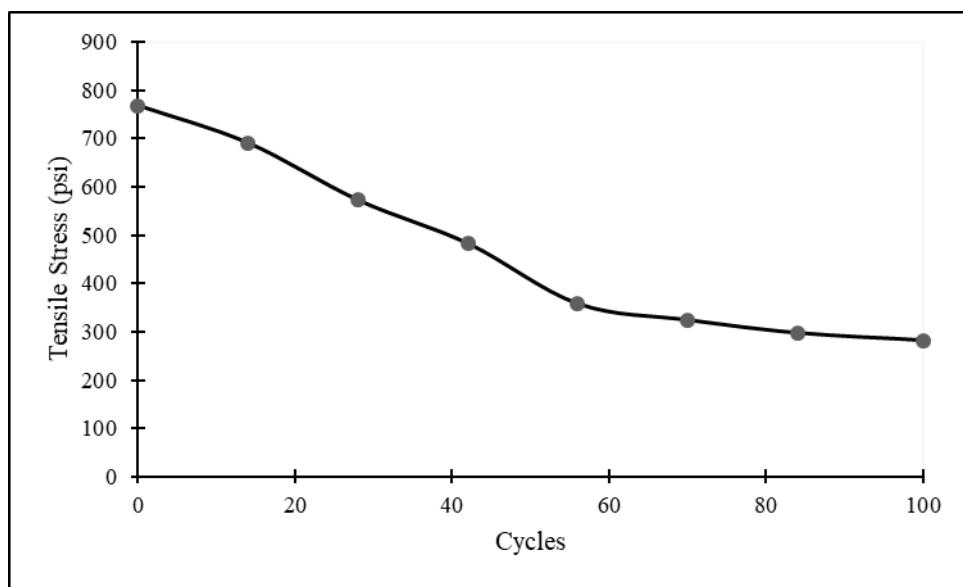
Figure 22. Direct Tensile Stress versus Number of Cycles: Coating 6

Based on the test results presented in Figures 17 to 22, the following observations can be made:

- For coatings that are less durable, the decrease in adhesion strength is rapid during the early periods of exposure. After 14 cycles of exposure, the weak coatings lost almost 40% of the adhesion strength as compared to less than 20% loss for the better coatings.
- Accelerated decrease in adhesion strength continues till the adhesion strength becomes a small fraction of the initial strength for the weaker coatings.
- For some coatings, the rate decrease becomes less after a few cycles. These coating could be considered as better than the weaker coatings. Field evaluation of these coatings over a 20-year period does support this observation.
- Coatings that had both organic and inorganic primers were found to be the best economical and field-applicable systems. These coatings had not only the lowest rate of deterioration but retained more than 50% of the original adhesion strength after 100 cycles of exposure.

Corrosion-Creep Growth

The adhesion strength results were used to estimate average creep growth using the procedure presented in section "*Interpretation in Pull-off Tests*". The variation of reduction in radius and average corrosion creep growth are presented in Figures 23 to 28 for the 6 coating systems.
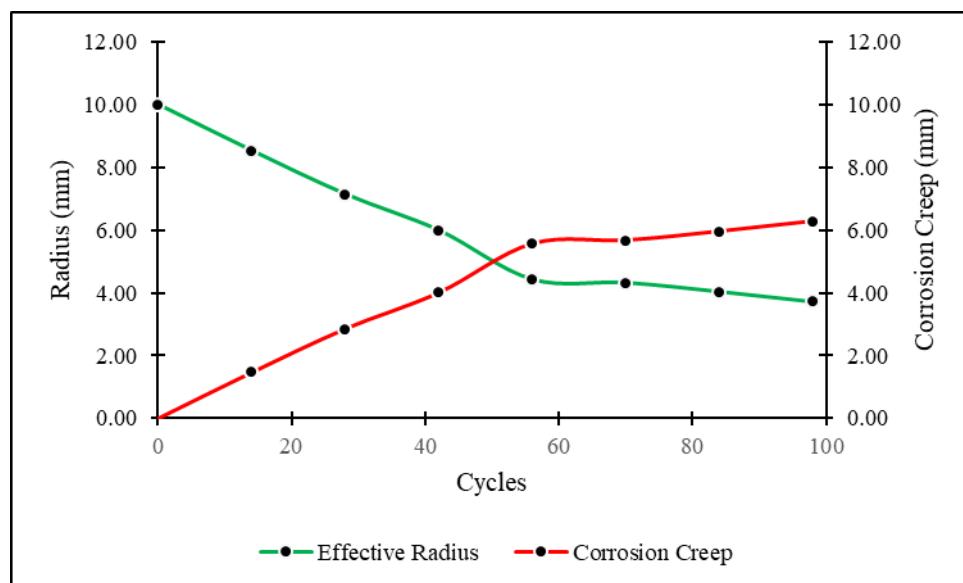
Figure 23. Effective Radius and Corrosion Creep Growth versus Number of Cycles: Coating 1
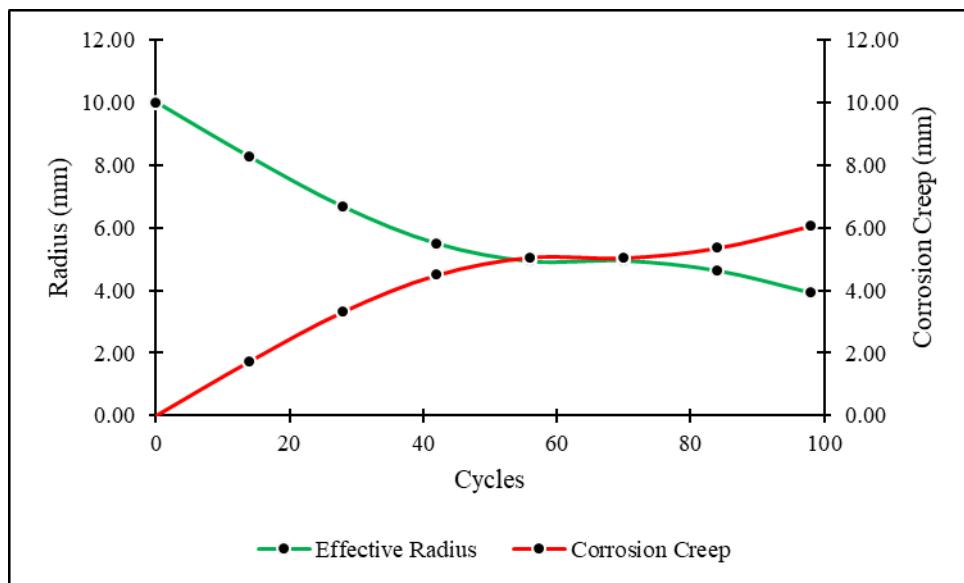
Figure 24. Effective Radius and Corrosion Creep Growth versus Number of Cycles: Coating 2
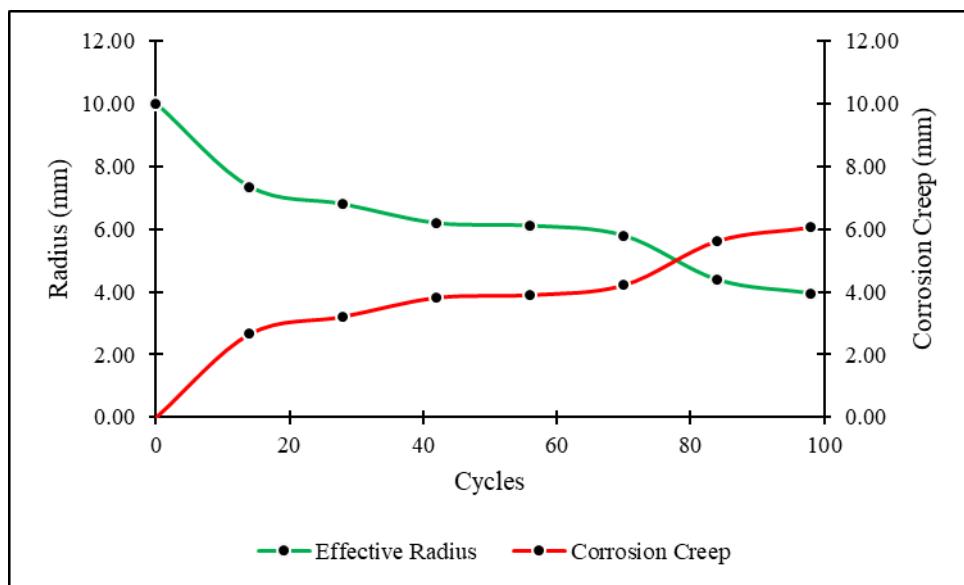
Figure 25. Effective Radius and Corrosion Creep Growth versus Number of Cycles: Coating 3
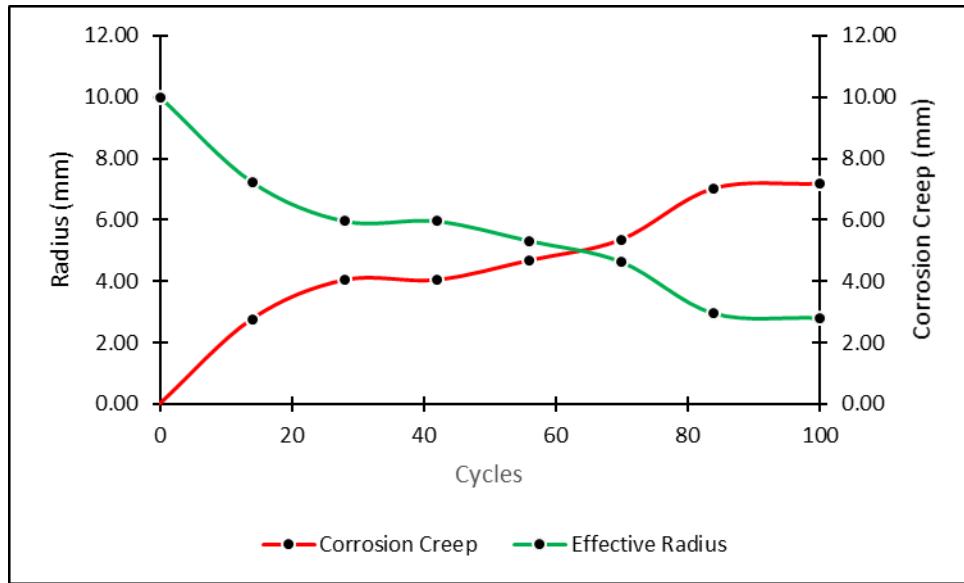
Figure 26. Effective Radius and Corrosion Creep Growth versus Number of Cycles:
Coating 4
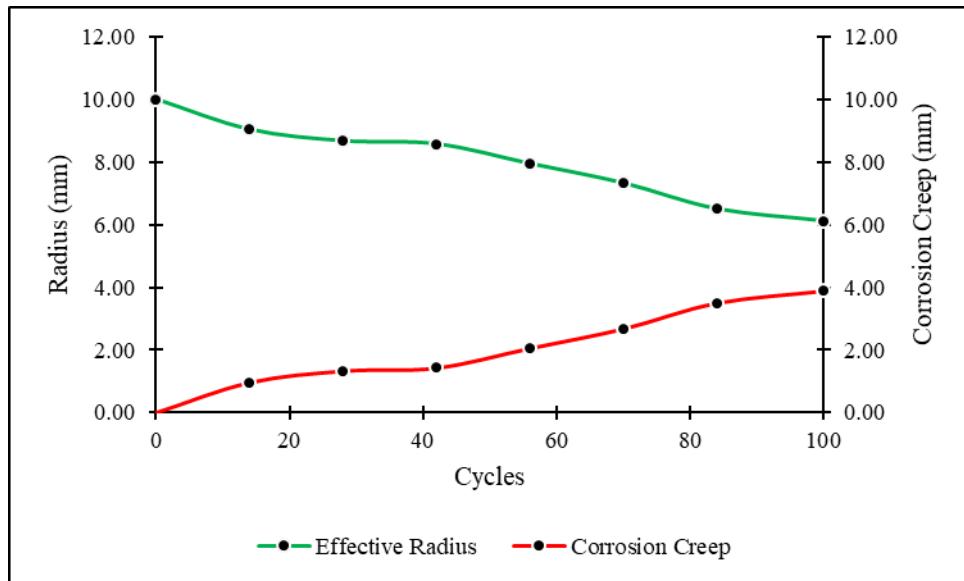
Figure 27. Effective Radius and Corrosion Creep Growth versus Number of Cycles:
Coating 5

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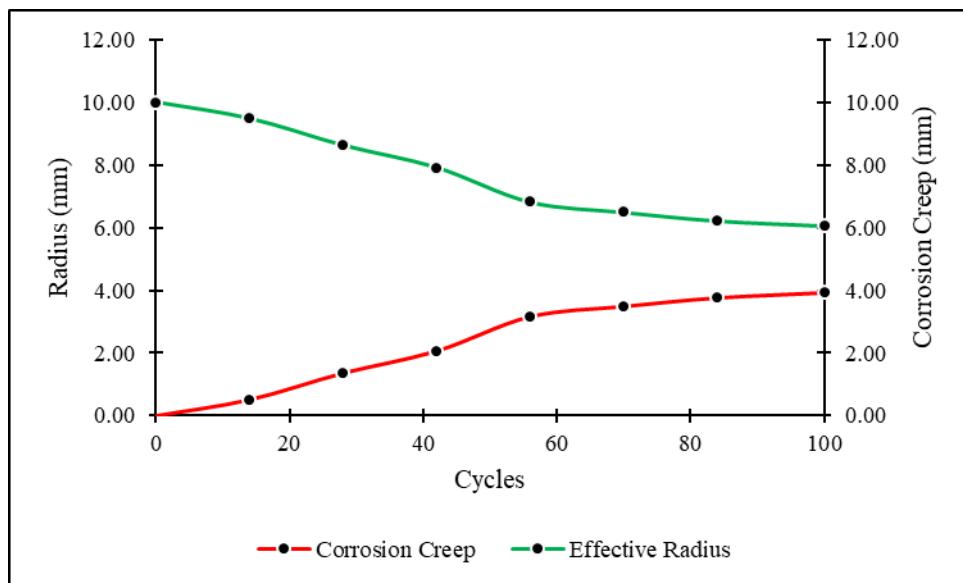
Figure 28. Effective Radius and Corrosion Creep Growth versus Number of Cycles: Coating 6

Since these results provide a different representation of the adhesion strength, the trends are the same. These graphs provide easier visualization for understanding the progress of deterioration and reinforces the observations made in earlier sections. Coatings 1 and 2 deteriorate rapidly under accelerated corrosion. Average creep growth at 14 cycles for these coatings were 1.6 mm. At 100 cycles of exposure, the corrosion creep increased to 6mm. Note that these coatings were judged to be weakest among the approved coatings of NJDOT. These numbers were 0.7 at 14 cycles and less than 4mm at 100 cycles for Coatings 4 and 5, that provided the best performance.
The results of the current study concur with the generally accepted perception that zinc-based primers provide the best protection against corrosion. The results also correlate well with a 20-year field-performance study carried out by New Jersey Department of Transportation.

Change in color
The readings of color meter taken at 0 and 100 cycles are presented in Table 5.

Table 5 - Color Recordings: Percent Change from Cycle 0 to Cycle 100

	Difference (%)		
	L*	a*	b*
System 1	2.0	-113.6	-423.7
System 2	3.2	-93.3	-25.5
System 3	0.4	-114.3	-137.8
System 4	0.4	-2.6	29.7
System 5	0.5	2.9	-12.5

The variation of a* and b* coordinates were random. Since the rusting resulted in deposits of impurities that affected these readings, these could not be used for evaluating the change in color. The variation of L* coordinates was consistent, and the maximum change was less than 5%. In addition, the change was less for the coatings that retained adhesion strengths. Therefore, it is recommended to use the change in L* coordinates for evaluating the coating performance. Based on the data obtained in this investigation, it is recommended to limit the change in L* coordinates to 10%.

Change in thickness

The average percentage change in thickness values at cycle 0 to cycle 100 are presented in Table 6.

Table 6 – Average Thickness Change

Thin Coating System	Average Thickness Change (%)
1	0.0
2	0.7
3	0.8
4	1.9
5	6.3

The magnitude of thickness change was less than 1% and therefore the change in thickness can be considered negligible. The number of exposure cycles were not sufficient to cause any substantial change in thickness. The results are consistent with the results reported in the literature. A large number of cycles are needed to cause measurable degradation in thickness. Therefore, it is expected that this parameter will not control the acceptance decision. However, in order to cover unusual cases, it is recommended to limit the reduction in thickness to less than 10%.

Deterioration Near Weld-Lines and Bolt-Holes

Results of visual inspection are presented in Tables 7, 8 and 9 for coatings 1, 2 and 3, respectively. There were no deteriorations for coatings 4 and 5 and the behavior of coating 6 was very similar to the coating 1.

Table 7 - Visual Inspection: Coating System 1

Coating System 1		
Specimen	Location of Deterioration	Cycle of Deterioration
1	Hole, Weld	42
2	Weld	42
3	Hole	56
4	Hole	42
5	Weld	42
6	Hole, Weld	42

Table 8 - Visual Inspection: Coating System 2

Coating System 2		
Specimen	Location of Deterioration	Cycle of Deterioration
1	Weld	42
2	Weld	42
3	Weld	42
4	Hole	42
5	Hole, Weld	42
6	N/A	N/A

Table 9 - Visual Inspection: Coating System 3

Coating System 3		
Specimen	Location of Deterioration	Cycle of Deterioration
1	N/A	N/A
2	Weld	42
3	Hole	42
4	Hole, Weld	42
5	Weld	42
6	Weld	42

From tables 7, 8 and 9, it can be seen that deterioration around bolt-holes and weld start around 42 cycles of exposure. N/A means that there was no deterioration. Once the deterioration starts, the damage expands during further exposure. These results confirm the weakness of coatings 1 and 2 identified in the adhesion strength results.

Summary of Field Evaluation Results of The Coatings

Results available on field evaluation of the durability of protective coatings are very limited. Typically, the structures are re-coated when the deterioration starts to occur. The condition of the coatings before re-coating are not documented. To the best of authors knowledge, the study conducted by NJDOT was the only source for extensive and detailed information on the duality of coatings after a long period of field-exposure. In this investigation 47 different coatings were evaluated over a period of 20 years. A few studies were conducted by Federal Highway Administration (FHWA) [18-26], Connecticut DOT [12], Virginia DOT [39], but the length of field exposure was limited to 5 years. This duration is very short as compared to a life expectancy of at least 25 years for a good coating system. Other studies done by U.S Navy [15] and a few state DOTs were limited to 1-year exposure. A short summary of the details and findings of NJ DOT study are presented in the following sections.

For the NJDOT Mathis Bridge [34] study, a number of coating systems were applied on various individual spans of the Thomas Mathis Bridge, located over the salt water of Barnegat Bay in Atlantic Ocean, with vertical clearances from 5 feet at the abutments to 33 feet at the lift span, during 1986 and 1987. This bridge has 66 spans plus a lift span with a span length of approximately 73 feet and contains five rolled I-beam stringers of A-36 steel spaced 8 feet apart. Each span has approximately 4,000 square feet of painted steel-surface area. Upon construction in 1950, the structure was painted with three coats of an oil-based paint containing red lead pigment and was repainted three times over the next 28 years. The painting work for 1986–87 evaluation replaced the coatings applied in 1978. The coating applied in 1978 consisted of: a basic lead-silico chromate, oil alkyd system with a pigmented fascia and black-graphite for the interior surfaces. An inspection of the bridge in 1984 revealed heavy rust and corrosion on bearing assemblies, some stringer webs, and bottom flange of the stringers. Corrosion was extensive on stringer ends located at the bridge piers, probably due to run-off water from the bridge deck expansion joints. Rust scale on the steel was as thick as 1⁄2-inch in some locations and concentrated salt deposits can be seen beneath the deck joints. This bridge was chosen for the evaluation of the coating systems because the coatings will be exposed to severe marine environment and road salt run-off, creating a severe corrosive environment. The coating systems for the study were chosen based on laboratory evaluation of available maintenance coatings.

Coating systems supplied by 18 manufacturers were applied on 47 of the 66 spans. The systems can be broadly grouped as: aluminum metallizing, zinc metallizing, inorganic and organic zinc primer-based coatings, epoxies, aluminum epoxy urethanes, vinyls, urethanes, oil-alkyds and mastics. The details of the 47 coating systems grouped into 8 generic categories are presented in Table 10. This table which was reproduced verbatim from Mathis Bridge Study [34] contains information on surface preparation, application date, and span number. The surface preparations ranged from economical and rapid SSPC-SP 2, Hand Tool Cleaning, to rigorous SSPC-SP 5, White Metal Blast. The surface preparation was chosen using recommendations of the manufacturers. For systems that specified spot cleaning, only loose rust and peeling paint were removed. Painting operations were carried out from mid-October to mid-November of 1986 and

April to October of 1987.

Table 10 - Summary of Test Coating Systems [34]

Span	Coating System	Surface Preparation	Application Date	1986 Cost($/ft^2)
	Alkyd Systems (6)			
7E	Alkyd Oil Base/Si Alkyd	SP-2	Nov. 86	$0.71
11E	Alkyd/Epoxy/Urethane	SP-2	Oct. 86	$1.04
21W	Alkyd/Epoxy/Urethane	SP-6	Aug. 87	$1.56
43W	Oil -Alkyd	SP-6	Oct. 87	$1.11
13W	Oil Alkyd-3 Cts	SP-2	June 87	$0.73
31W	Oil-Alkyd	SP-6	Oct. 87	$1.37
	Aluminum Systems (8)			
41W	Alum. Urethane/Acryl.	SP-6	Sep. 87	$1.58
12E	Alum. Epoxy/Urethane	SP-7	Oct. 86	$1.00
9E	Alum. Epoxy/Urethane	SP-2/3	Nov. 86	$0.63
8E	Alum. Epoxy/Urethane	SP-2	Nov. 86	$1.07
6E	Alum. Epoxy/Urethane	SP-2	April 87	$0.6
5W	Alum. Epoxy/Urethane	SP-2	May 87	$0.7
45W	Alum. Epoxy/Urethane	SP-6	Oct. 87	$0.82
24W	Alum. Ureth./Urethane	SP-6	Sept. 87	$1.28
	Epoxy Systems (6)			
9W	Epoxy Mastic/Epoxy Mast.	SP-6	June 87	$1.00

17W	Epoxy Mastic/Urethane	SP-6	July 87	$1.25
18W	Epoxy/Urethane	SP-6	July 87	$1.29
32W	Epoxy/Urethane	SP-6	Oct. 87	$1.12
27W	One Coat Epoxy	SP-6	Sept. 87	$0.69
29W	One Coat Epoxy	SP-6	Oct. 87	$0.99
	Inorganic Zinc Systems (8)			
34W	H_2O Inorg. Prime/Silicone	SP-6	Oct. 87	$1.67
30W	H_2O Inorg. /Acryl	SP-10	Oct. 87	$1.99
42W	Inorg. Zinc/Vinyl	SP-10	Oct. 87	$1.56
46W	Inorg. Zinc/Vinyl	SP-10	Oct. 87	$1.26
14W	Inorg. Zinc/Epoxy/Ur.	SP-6	June 87	$1.85
35W	Inorg. Zinc/Epoxy/Uret.	SP-10	Oct. 87	$1.94
39W	Inorg. Zinc/Urethane	SP-6	Oct. 87	$1.07
12W	Inorg. Zinc/Vinyl	SP-10	June 87	$1.75

Performance evaluation of the coatings were done after 1, 8 and 20 years. The 1-year performance evaluation was carried out by NJDOT in-house team consisted of inspecting the bottom flange from a boat to identify the weak coatings. The 8 and 20-year performance was rated in accordance with ASTM D610 [8], Standard Method of Evaluating Degree of Rusting on Painted Steel Surfaces. Three inspectors performed visual inspection from a boat in 1995 (8-year study) by assigning a 1–10 rating to the entire span in accordance with ASTM D610 [8]. The ratings of the 3 inspectors were within one unit for most of the spans and these ratings were averaged to obtain a composite rating. The inspection was repeated in 2017 (20-year study) using the procedures of 1995 inspection.

The results of 1-year evaluation showed failure of a few systems, even within this short exposure period. All the failed systems were applied over an SSPC-SP 2 (hand-tool cleaned) surface. Some systems such as calcium borosilicate-pigmented alkyd system

and an oil-alkyd system, applied over SP 2 prepared surfaces did perform well. The results for systems applied over abrasive blasted surface were consistently good and there were very little differences between systems.

The results of 8 and 20-year evaluation are summarized in Table 11. The performance was rated using the rating numbers 0 to 10. The number 7 and higher means the rusting was limited to 0.3% and no intervention is necessary. Numbers decreasing from 7 to 4 indicates the growth of rust area from 0.3% to 10% and some maintenance over-coating may be needed to prevent further deterioration. Numbers less than 4 with more than 10% rusted area are considered as failure and re-coating might be necessary. A reasonable definition of a successful coating system might be one that is 7 or better at 8 years and 4 or better at 20 years.

Table 11 – Distribution of Condition Ratings for Coating within Each Category

	D610 Rating at 8 Years			D610 Rating at 20 Years		
	>7	7-4	<4	>7	7-4	<4
Metallizing Systems (2)	2	0	0	2	0	0
Inorganic Zinc Systems (8)	7	0	1	2	5	1
0rganic Zinc Systems (7)	5	2	0	2	4	1
Miscellaneous Systems (5)	3	2	0	1	3	1
Alkyd Systems (6)	4	2	0	1	3	2
Urethane Systems (5)	2	3	0	1	2	2
Aluminum Systems (8)	1	4	3	0	4	4
Epoxy Systems (6)	0	4	2	0	0	6

The comparative performance of the 8 groups of coatings after 8 and 20 years of exposure are presented in Figures 29 and 30. In these figures the percentage of coatings within a chosen category that performed extremely well (Excellent, rating 7 or higher), reasonably well (Good, rating 4 to 7) and poorly (Poor, rating 4 to 0) are shown in the Y axis. For example, there were 8 coatings in Inorganic Zinc group. After 8 years of exposure, 7 out of 8 or about 90% provided excellent performance and after 20 years of exposure the percentage of coatings that provided excellent performance dropped to 25%. But even after 20 years of exposure only one coating system failed.
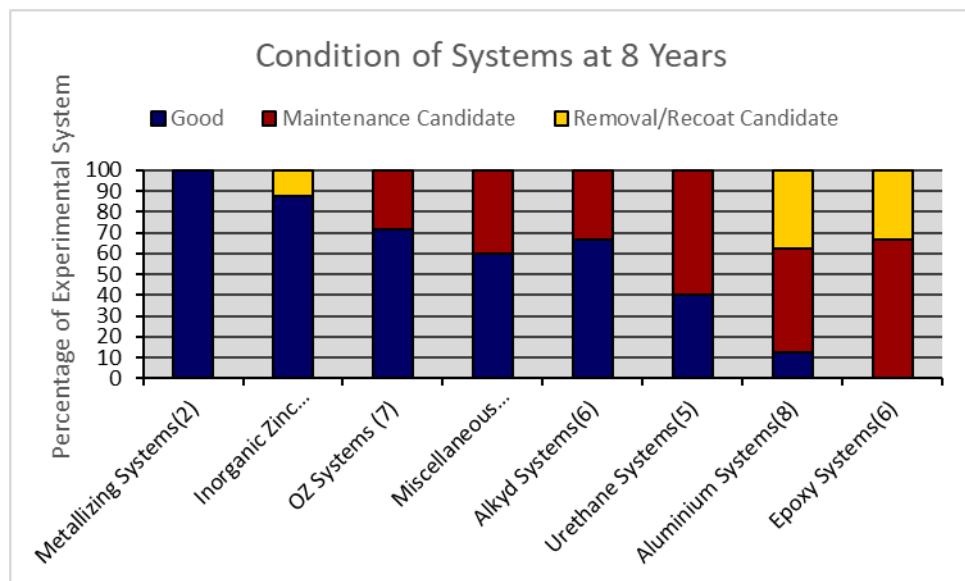
Figure 29. Condition of Systems at 8 Years from Mathis Bridge Study
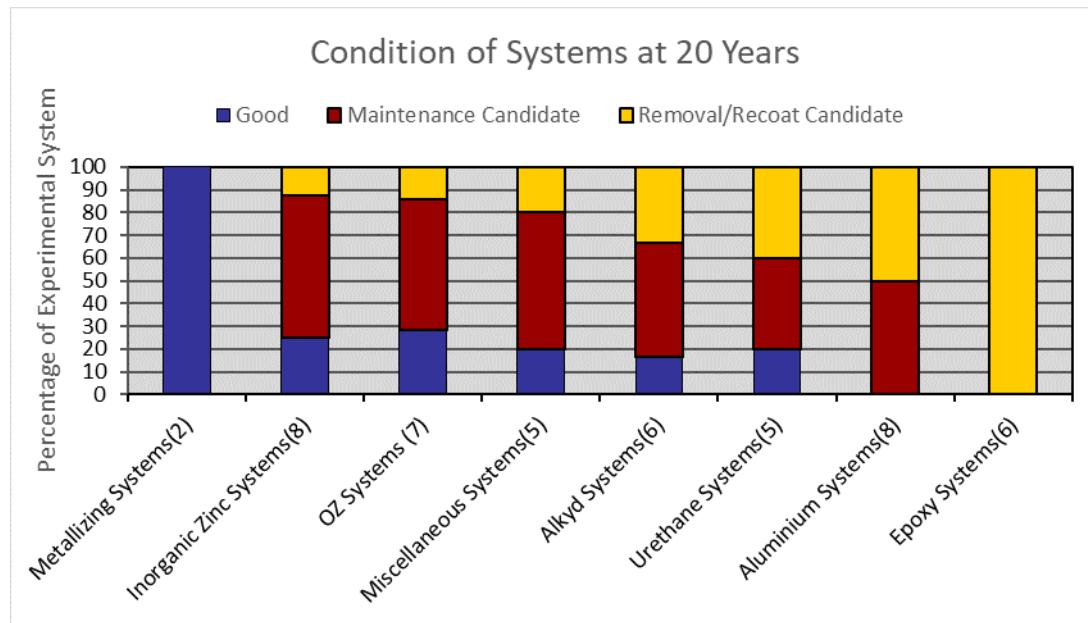
Figure 30. Condition of Systems at 20 Years from Mathis Bridge Study

A careful review of the results presented in Table 11 and Figures 29 and 30 and the information obtained after only 1 year, lead to the following observations:

- The epoxy mastic systems showed notably poor performance. The deterioration started after 1 year and continued rapidly as shown in Figure 30. After 8 years of exposure none of the systems had a rating higher than 7 and after 20 years of

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exposure all the coatings had a rating less than 4. Poor performance of mastic coatings was also reported by other investigators.

- Even though the coatings showed varied levels of deterioration, coatings with zinc primers performed better than the other coatings, except metallized coatings. Out of 15 coatings, 4 systems had a rating greater than 7 even after 20 years of exposure.
- The best performing metallized coatings were very expensive, not readily available and not suitable for over-coating applications [34].
- In summary, it can be stated that the best performing economical coatings are the systems with zinc primers and worst performers are epoxy mastic systems. It is interesting to note that almost all state DOTs specify zinc primers for most of their coating applications.

The information learned from this study was used for selecting the coating systems for evaluation of the proposed protocol. The following are the key points used for selecting the 6 coatings used in the current accelerated testing:

- Metallizing systems were the best, but these were not selected for the current investigation because they were very expensive and not readily available.
- Systems with organic and inorganic primers were next best and these were chosen for the current evaluation. The accelerated tests also showed that these are far better than epoxy mastic systems. The performance-parameters of these coating systems were used to develop the acceptance criteria for NJ DOT.
- Epoxy mastic systems were the worst performers. Two epoxy mastic systems used in the current study also showed rapid deterioration.
- Another system that was better than the mastic but not as good as systems with zinc primers were also chosen for the current investigation. Accelerated tests also showed similar performance.

Correlation of Laboratory and Field Test Results

The laboratory study results obtained using the proposed test protocol are consistent with the long-term field performance. The similarities are highlighted in the following observations:

- The systems that performed best in the field, namely, systems with zinc primers also performed best in the accelerated test study. The creep growth for coatings with zinc primers were about 4 mm after 100 master cycles whereas the worst performing epoxy mastic systems had a creep growth in excess of 6 mm.
- As in the case of filed performance, the level deterioration measured in terms of creep growth at the earlier stages exposure were also much higher for epoxy mastic systems. The slope of the deterioration curves at the early stages were steep both in the accelerated test and field evaluation as shown in Figures 17 and 30.

- The coating system that had non-zinc primer had better performance as compared to epoxy mastic systems and not as good as the systems with zinc primers. This is also consistent with the results of the field study.

In summary, it can be stated that the proposed protocol for accelerated testing simulated the field performance well. When more data become available, it might be possible to correlate the laboratory and field results and develop a model to predict the life of a coating in the field using laboratory test results.
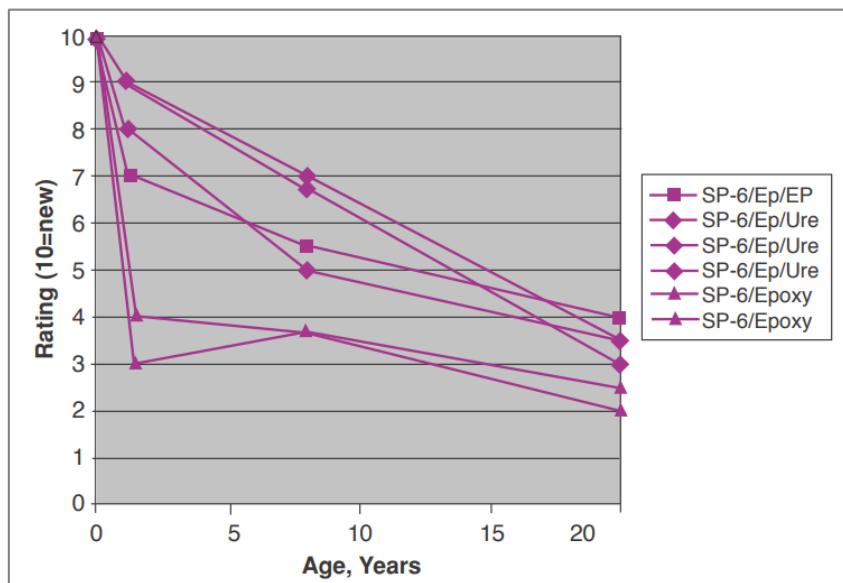

Figure 31. 20-Year Performance of Epoxy Systems from Mathis Bridge Study [34]

Proposed Acceptance Criteria

An acceptance criterion to better determine the over coating paints effectiveness in actual field conditions has been established from the results of the developed protocol. The acceptance criteria are based on the results of the response variables of pull off tests, color change, thickness change and visual inspections. For the results of the pull off tests, any specimen at 42 cycles with a corrosion creep greater than 2.5 millimeters will be rejected. At the completion of 100 master cycles, any specimen with a corrosion creep greater than 5 millimeters will be rejected. Any specimen after 100 master cycles with a color change or thickness change greater than 10 percent will be rejected. Any significant deterioration changes detected by visual inspection will result in the rejection of the specimen. However, if the over coating system remains within the allowable limits of the corrosion creep, color change, thickness change and visual inspection; the over coating paint system is accepted.

Quality Assurance

Research Approach

The New Jersey Department of Transportation requires all contract materials from any roadway construction or job site to be tested and approved according to their specifications. Testing is essential to ensure that structural steel paints are not adversely modified or altered. The most efficient and timely method of testing such materials is by using an Infrared Spectrophotometry Scan (IR Scan) specified in ASTM E 2937. This method was adopted by NJDOT as well as many other state DOTs for quality control of these paints. This type of test provides verification that the material sampled and tested from a site is identical to the same material originally submitted, approved, and listed on the qualified producer/supplier list. Differences sometimes occur in IR spectra between various batches of structural steel paints delivered to the department from the site and the original approved materials. It is not certain what causes these differences or the effects on concrete and steel when using modified or altered paints with non-conforming spectra. There are several potential reasons for the non-conforming spectra such as, change in formulation, presence of contaminants, improper storage, improper labeling, etc. It is therefore especially important to be certain all materials used in a project conform to the standard, avoiding potential performance deviation of a material on the job site.

Table 12 - NJDOT Qualified Producer/Supplier (QPL) list of structural steel paints

| LIST of Paints |
|---|
| Aluminum II Part A |
| Aluminum II Part B |
| Interplast 356-part A |
| Interplast 356-part B |
| Devathane 359-part A |
| Devathane 359-part B |
| HS Polyurethane Part S White |
| HS Polyurethane Part T Hardener |
| Carbothane 133 LV Part A White |
| Carbothane 133 LV Urethane Converter |
| Carbomastic 615 AL Part A |
| Carbomastic 615 AL Part B Urethane Converter |
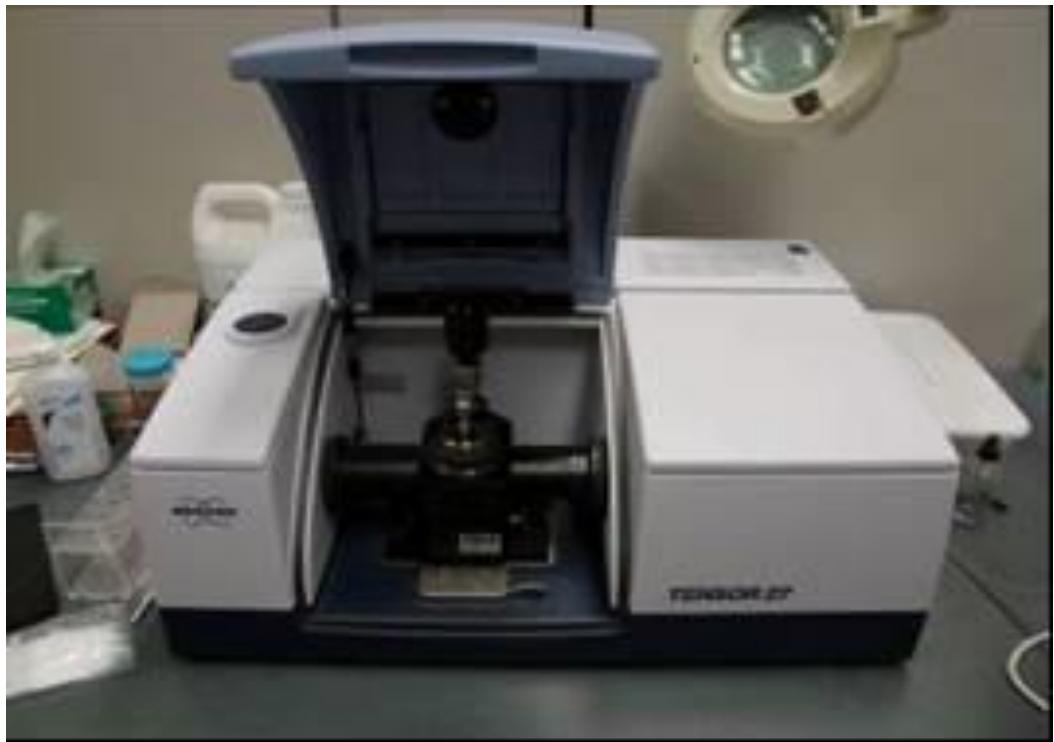
Figure 32. The Perkin-Elmer Infrared Spectrometer.

Infrared Scan Methodology for Structural Steel Paints

Infrared spectroscopy for structural steel paints was performed using an infrared spectrometer similar to the one shown in Fig. 32. Infrared spectra tests were performed on samples obtained from the manufacturer for various types of paints given in Table 1.

Procedure for IR scan of structural steel paints

The IR scan of structural steel paints followed the following steps:

- Identify structural steel paint to be scanned.
- Place a small paint sample in a can and insert the paint can into an automatic paint shaker for a duration of 3 minutes.
- Open the can and briefly hand mix the paint with a mixing stick to ensure a uniform sample distribution.
- Set up the infrared spectrometer and run a background scan of the clean lens.
- Using a pipette, evenly coat the lens in a layer of paint. It is especially important to be certain the entire lens is covered to prevent light from affecting the scan.
- Run the machine to obtain the infrared absorption spectra.
- Two scans are performed for every sample from each batch.

Data files then were processed to obtain correlation coefficients as explained in the next section.

Test Results and Discussions of IR Scans of Steel Paints

The IR scan of structural steels was relatively simple. The procedure included several simple steps as explained earlier that resulted in two scans from each batch. Two IR scans from each batch of steel paints were performed (scan 1 and scan 2). This resulted in a total of four scans from the two batches. For each scan the absorption versus the wave number was recorded and tabulated in an Excel spreadsheet. Typical IR scans for steel paints for INTERPLAST 356 PART B are shown in Figure 33. The figure shows consistent peaks and valleys of the IR scan from all three batches. Similar IR scans were observed for structural steel paints.
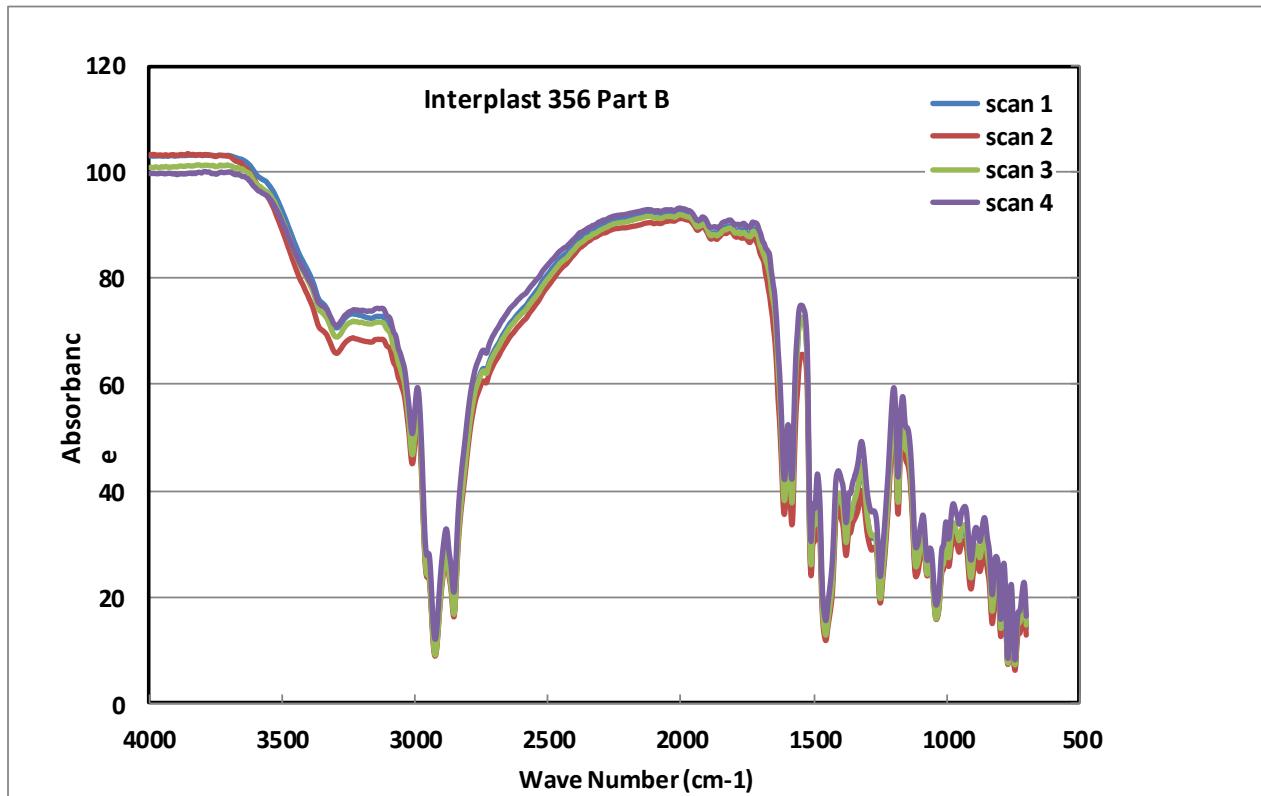

Figure 33. Plot of four (4) IR scans of Interplast 356 Part B from two batches

The formula used to determine the correlation coefficient for a typical paint system S is the following:

$$CORREL(X,Y) = \frac{\Sigma(X - \bar{X})(Y - \bar{Y})}{\sqrt{\Sigma(X - \bar{X})^2(Y - \bar{Y})^2}}$$

Where,
X= absorbance values of scan A of paint S
$\bar{X}$ = average of the absorbance values of scan A of paint S
Y= average absorbance values of all scans from all three batches of paint S
$\bar{Y}$= average of the average absorbance of all scans from all three batches of paints S

The correlation factor of the six scans was determined and is shown in Table 13. With the exception of Interplast 356 Part A, steel paint correlation factors were all higher than 0.98. As mentioned earlier, the correlation coefficients for steel paints were determined as follows: two scans from each batch were generated for a total of four scans, then the average IR scan was determined from all four scans. Then the correlation coefficient was determined for each scan with respect to the average. These correlation coefficients were then averaged to obtain the average correlation coefficient for that particular steel paint. Table 13 shows the average correlation coefficients for the individual steel paints.

Table 13. Correlation coefficients for steel paints

PAINT SYSTEM	Correlation Coefficients
Aluminum II Part A	0.99634
Aluminum II Part B	0.99939
Interplus 356 Part A	0.97763
Interplus 356 Part B	0.99948
Devathane 359 Part A	0.99985
Devathane 359 Part B	0.99967
HS PolyUrethane Part S White	0.99897
HS PolyUrethane Part T Hardner	0.99943
Carbothane 133 LV Part A White	0.99926
Carbothane 133 LV Urethane Converter	0.99905
Carbomastic 615 AL Part A	0.99967
Carbomastic 615 AL Part B Urethane Conve	0.99921

CONCLUSIONS AND RECOMMENDATIONS

Based on the findings of this investigation, the following conclusions can be drawn:

- The new test protocol does provide quantitatively measurable results for measuring corrosion vulnerability and the results also correlate with the field results of New Jersey Department of Transportation study (Mathis Bridge).
- Of the coating systems currently in use, those containing an inorganic zinc or organic zinc primer performed best. The epoxy systems and aluminum-mastic systems performed worst.
- The newly developed protocol for accepting new over coating systems is based on the concept of currently used scribe but applies an O-ring during painting to form the outline of the scribe. After the over coating paint cures, the O-rings are removed, exposing the steel with no damage to the over coating paint or steel specimen.
- The new testing procedure provides a guideline to estimate the average corrosion creep based on the specimens pull off strength. There is no scraping of the specimen's paint or subjective corrosion creep measurement required.
- The effectiveness of an over coating system can be analyzed within three months.
- Acceptable correlation coefficients were established based on four scans from two batches for each steel paint for quality assurance.
- The correlation coefficients for structural steel paints were more consistent and had less variation. With the exception of paint system Interplast 356 Part A, steel paint correlation factors were all higher than 0.98.

It is strongly recommended that the proposed protocol be implemented by NJDOT for accepting new coating systems. It is also recommended to make an effort for convincing other DOTs to adopt the new protocol. The authors propose to conduct a Pool Fund study in collaboration with other states to achieve this goal. This aspect is further elaborated in the next section.

IMPLEMENTATION PLAN

Objective

The primary objective is to develop a systematic procedure for reviewing and accepting new coating systems. The plan includes provision for obtaining acceptance for the proposed protocol from a wider pool of States through pool fund study. If the coating is accepted, it will be added to the NJDOT approved list of coatings. The focus of the current plan is for over-coating systems and implementation of a new test protocol. However, the procedure can also be used for new coatings with minor modifications.

Outline of the Plan

Two main activities are envisioned for implementing the plan. The first activity will focus on obtaining support and concurrence for the proposed protocol from other State DOTs. It is envisioned that a Pool Fund study will be needed to establish the repeatability of the proposed test method by conducting a round-robin study, possible refinements and overall acceptance of the protocol. Positive and enthusiastic response was received when the preliminary results were presented in 2018 Transportation Research Board (TRB) meeting. Considerable interest was expressed by officials at two DOTs and FHWA to develop the proposed system for nation-wide use. It is proposed to develop a plan for achieving this using the following steps:

- Prepare a survey questioner to determine interest and participation various State DOTs in the pool fund study. Background information will be provided regarding the test method and the acceptance protocol. The survey questions will focus on their current practice, their perception for the need for broad-based acceptance protocol for coatings, willingness to participate in pool fund study, possibility for providing other technical/scientific contributions including running round-robin tests and serve on a Panel to advice for the development and acceptance of the final Protocol. Personal contacts will be made during 2019 TRB Meeting.
- Once the interested parties and their level of interest are identified, NJDOT will make a decision on initiating the pool fund study.
- If the decision is to proceed with pool fund study, an RFP will be developed using the standard procedure and input from the collaborating agencies.
- Conduct the research including the round robin accelerated tests for a selected coating system.
- Prepare an Acceptance Protocol based on the knowledge generated by the pool fund study.
- At the conclusion of the pool-fund study, establish a test and acceptance protocol agreed upon by all the participating agencies.

Implementation of this and possibly refined final protocol will be the second activity. Rutgers team will work with NJDOT team to develop all the detailed steps necessary for the full implementation, including a mock-up test run.

Envisioned Major Steps (Tasks) for Implementation

This task is expected to be performed in parallel to the effort for obtaining support from other states. The following steps are envisioned for the implementation. These steps will

be fine-tuned using the information obtained from the final report and input from NJDOT.

1. Formation of a working group for approving new coating systems
2. Charge for the Working Group:
3. Outline of various steps for approval:
   - Initial Contact
   - Providing information to companies looking for approval
   - Receiving report and checking the compliance with the specification to be proposed.
   - Initial review
   - Review by the working group
   - Final approval
4. Communication of the decision and close-out
5. Field performance of the process
   - Review the performance of new coating 2 to 5 years using inspection data
   - Collect information of best and worst coatings
   - Remove coatings from the approved list based on field performance.

After the initial review of these tasks and input from NJDOT, these tasks will be revised. A short report will be prepared for the implementation process.

Another major task is the presentation of the acceptance procedure and the basic details of the protocol in a workshop format for the individuals identified by the NJDOT. It is expected that the duration of this workshop will be 2 or 3 days.

Deliverables

1. Preparation of draft survey and refined version based on input from NJDOT.
2. Preparation of summary of responses and recommendations for further action.
3. Any needed input for pool fund study including RFP.
4. Provide support to NJ DOT team responsible for approving the new coatings throughout the implementation process (Steps).
5. Quarterly reports and meetings and other meetings of workshops as necessary.
6. Rutgers team can provide assistance to carry out the entire process.

REFERENCES

1. AbdelRazig, Y.A. and C. Luh-Maan, "Intelligent Model for Constructed Facilities Surface Assessment." Journal of Construction Engineering & Management, 2000. 126(6): p. 422.
2. Appleman, B., 'Effects of Surface Contamination on Coating Life.' FHWA: Washington, D.C., 1991.
3. ASTM G154-16, "Standard Practice for Operating Fluorescent Ultraviolet (UV) Lamp Apparatus for Exposure of Nonmetallic Materials", ASTM International, 2016, West Conshohocken, PA.
4. ASTM Standard B117-16, "Standard Practice for Operating Salt Spray (Fog) Apparatus", ASTM International, 2016, West Conshohocken, PA.
5. ASTM Standard D4541-17, "Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers", ASTM International, 2017, West Conshohocken, PA.
6. ASTM Standard D5065-07, "Standard Guide for Assessing the Condition of Aged Coating on Steel Surfaces- 17", ASTM International, 2009, West Conshohocken, PA.
7. ASTM Standard D5894-16, "Standard Practice for Cyclic Salt Fog/UV Exposure of Painted Metal, (Alternating Exposures in a Fog/Dry Cabinet and a UV/Condensation Cabinet)", ASTM International, 2016, West Conshohocken, PA.
8. ASTM Standard D610-08, A., "Standard Practice for Evaluating Degree of Rusting on Painted Steel Surfaces", ASTM International, 2009, West Conshohocken, PA.
9. ASTM Standard D6944-15, "Standard Practice for Determining the Resistance of Cured Coatings to Thermal Cycling", ASTM International, 2015, West Conshohocken, PA.
10. Ault, J., and C. Farschon. "Selecting and sourcing Bridge Coating Systems." Journal of Protective Coatings & Linings, 2011.
11. Beck B., *Evaluation of Minimal Surface Preparation Coatings for Bridge Painting.* MDOT, Research Report R-1394, May 2001.
12. CDOT *Field Evaluation of Zinc-Based Protective Coatings for Structural Steel - Final Report.* Connecticut DOT, October 1995.
13. Chmiel A., V. Mottloa, and J. Kauffman, 'Research on Structural Coatings Performance by New Jersey Department of Transportation.' Presented at the 6th International Bridge Conference and Exhibition, Pittsburgh, PA, 1989.
14. Chmiel A., V. Mottloa, and J. Kauffman, "Structural Coating Evaluation in New Jersey, Research News." Journal of Protective Coatings, January 1989, pp. 23–26.
15. David W. Taylor. 'Corrosion Barrier Coatings: One-year Evaluation of Marine Coating Exposures.' U.S. Navy, Research and Development Center, 1985.
16. Ellor, J., and Kogler, R., "Evaluation of Selected Maintenance Coatings over Hand and Power-tool Cleaned Surfaces." Journal of Protective Coatings and Linings, 1990.
17. Farschon C.L. and R.A. Kogler, "Field Testing Maintenance Overcoating Systems for Bridges.", *Journal of Protective Coatings*, January 1997, Volume 14, No. 1, pp. 56–67.

18. FHWA. Chong, S.L., and Y. Yao. Selecting Overcoats for Bridges: FHWA Researchers Test the Corrosion Resistance of Various Paint Systems for Steel Structures. In Public Roads, Publication FHWA-HRT-07-006, Vol. 71 No. 2 , FHWA, Washington, D.C., 2007.
19. FHWA. *Comparison of Laboratory Testing Methods for Bridge Coatings.* Publication FHWA-RD-94-112.
20. FHWA. Farschon C.L., R.A. Kogler, and J.P. Ault *Guidelines for Repair and Maintenance of Bridge Coatings: Overcoating.* Publication FHWA-RD-97-092, August 1997.
21. FHWA. *FHWA Bridge Coatings Technical Note: Overcoating.* FHWA, U.S. Department of Transportation, Editor. 2000: Washington, D.C., 1997
22. FHWA. Kodumuri, P., and S.K. Lee. *FHWA 100-Year Coating Study.* Publication FHWA-HRT-12-044, November 2012.
23. FHWA. Lee S.K., Y. Yao, S.L. Chong. *Performance evaluation of bridge overcoating materials using electrochemical impedance spectroscopy*, FHWA, 2006.
24. FHWA. *Performance of Alternative Coatings in the Environment (PACE); Volume I: Five-year Field and Bridge Data of Improved Formulations.* Publication FHWA-RD- 89-235.
25. FHWA. *Performance of Alternative Coatings in the Environment (PACE); Volume II: Five-year Field and Bridge Data of Improved Formulations.* FHWA Publication No. FHWA-RD- 89-235.
26. FHWA. *Steel Bridge Design Handbook: Corrosion Protection of Steel Bridges.* Publication FHWA-IF-12-052, Vol. 19, November 2012.
27. Hopwood T., and B. Meade, *Experimental maintenance painting by overcoating on the I-64, I-71, and KY-22 Bridges.* Kentucky Transportation Cabinet, Research Report KTC-99-51, July 1999.
28. Hopwood T., S. Palle, and R. Younce, 'Environmental Impacts of Bridge Cleaning Operations.' K.T.R. Center, Editor. 2003.
29. Kogler, R., and G. Washer, 'Experience Inspecting New York City East River Bridges.' Editor: Falls Church, VA, 2010.
30. Mitchell M.J., D. Claydon, D. Ward, "A Critical Review of Current Performance Tests for Offshore Anti- Corrosive Coatings", Corrosion '05, NACE Paper No. 05021.
31. MoDOT, *An Evaluation of MoDOTs Current Coatings Programs: Final Task Force Report.* Missouri DOT, Bridge Coatings Task Force, December 30, 2008.
32. Myers, J., W. Zheng, and G. Washer, *Structural Steel Coatings for Corrosion Mitigation.* MoDOT, Report No. OR-006, October 2010.
33. NEP-OVER-COAT-Qualified Products – List M, 5/7/2003
34. NJDOT *Structural Coatings Performance Evaluation (Mathis Bridge Study).* New Jersey DOT, Bureau of Materials Engineering and Testing, Revised. October 1995.
35. NYSDOT, *Special Provision 573.1018NN11, Field Cleaning and Painting of Steel Bridge Railing (previously painted).* New York State DOT.

36. O'Donoghue M., P. Roberts, and V.J. Datta, "Overcoating lead-based alkyd paint on steel penstocks: practical experience." Journal of Protective Coatings & Linings, August 2009.

37. O'Donoghue M., R. Garrett, V.J. Datta, "Overcoating Lead-Based Paint on Bridges: An overview of different coating options", Materials Performance, NACE International, September 2002.

38. O'donohugh, D., 'Overcoating Lead-based Paint on Bridges.' Materials Performance, 2002.

39. Stephen R. Sharp, Ph.D., P.E., Bridget M. Donaldson, Jeffrey L. Milton, and Curtis W. Fleming. *Preliminary Assessment of Procedures for Coating Steel Components on Virginia Bridges.* Report No.: VC FHWA/VCTIR 14-R1 4. TIR 14-R1 9, October 2013.

40. The Society for Protective Coatings, A. *SSPC- VIS 2 Standard Method of Evaluating Degree of Rusting on Painting Steel Surfaces.* 2000.

41. The Society for Protective Coatings. "Technology Update No. 3: Overcoating." SSPC 1997.

42. Tinklenberg, G., *Alternate Paint Systems for overcoating.* NHDOT, Report No. SPR-PL-PR-1(31) Project 12323 D, October 2000.

43. TRB. "Steel Bridge Maintenance Painting - A Synthesis." Transportation Research Board, Unpublished DRAFT, 1996.

44. USARMY- CERL Report prepared by BIRL-Northwestern Univ. 1996.

45. Zayed, T.M., C. Luh-Maan, and J.D. Fricker, "Life-Cycle Cost Based Maintenance Plan for Steel Bridge Protection Systems." Journal of Performance of Constructed Facilities, 2002. 16(2): p. 55.

46. Zayed, T.M., C. Luh-Maan, and J.D. Fricker, "Statewide Performance Function for Steel Bridge Protection Systems." Journal of Performance of Constructed Facilities, 2002. 16(2): p. 46.