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Implementation of a Protocol for Acceptance of New Over-Coating Systems for Steel Surfaces

Final Report
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Submitted by

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16. Abstract

This project was undertaken to develop a procedure to accept new coating systems for over-coating of steel surfaces and the results are presented in three parts. Section I and Section II covers acceptance procedure and details of information needed based on accelerated corrosion test. Section III presents a model for predicting field service life using the accelerated test results. Key steps of acceptance procedure are: (i) Submission of basic information for initial review, (ii) The required test results for evaluation, (iii) Initial approval and addition in the QPL as provisional candidate and (iv) Final approval after obtaining field data for a minimum of 2 years.

Detailed guidelines are presented in the second section for conducting accelerated environmental exposure tests and reporting the information needed for approval. The new test method is based on direct pull-off (adhesion) strength at various stages of corrosion and provides clearly measurable degradation within three months of accelerated exposure. The results show a clear difference between the best and the poor coatings and also correlate well with results of long-term field study.

A model for predicting the service life of coatings using the accelerated test results, presented in Section III is based on the science of corrosion, models available in existing literature and information available on field performance. The model can be used to estimate the service life new formulations using accelerated test results that can be completed within one year.

17. Key Words Over-coating, accelerated testing, steel surfaces, corrosion growth, field performance	18. Distribution Statement

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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 were the key conclusions.

- 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

In the current project an implementation procedure was developed. Details of the procedure is presented in this report. The report consists of three parts. The procedure for acceptance of a new coating system by NJDOT is presented in Section I. Section II covers the details of the experimental procedure and results to be presented to NJDOT approval committee and Section III presents a procedure for predicting field service life using the accelerated test results.

It is also recommended to update Section 912.01.01 with the following statement.
912.01.01 Structural Steel Paint
Use paint systems for coating structural steel that are Northeast Protective Coating Committee (NEPCOAT) approved and listed on the QPL. Use the appropriate paint type for the application as follows:
1. Use an inorganic zinc, epoxy, urethane (IEU) paint system for coating new structural steel.
2. Use an organic zinc, epoxy, urethane (OEU) paint system, or a New Over-Coating paint system for over-coating existing structural steel.

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. 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 of this effort was presented in a research report. 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

The current project was undertaken to implement the new protocol for accepting new over-coating systems by NJDOT. The implementation project was initiated in May 2019 and was slated to be completed by February 15, 2021. While the implementation process was in progress, the project was selected as one of the Sweet 16 Projects by FHWA. This National recognition came with some additional tasks such as two poster-presentations. The project also won Implementation Award from NJDOT. These recognitions provided opportunity for more dissemination and obtain input from more researchers and state DOT. The results were presented in a number of meetings including: TRB Committee on Corrosion, as a paper in TRB 2019, in a regional meeting of DOTs in Michigan, and poster sessions for FHWA and TRB 2020. Another presentation was made in a SSPC conference in California.
The protocol was well received in all the five presentations. In addition to acceptance testing, the protocol can also be used to develop new coating systems. New formulations can be evaluated quickly and economically to select the coatings with better potential. This aspect will not only increase the use and acceptance of the test method by coating manufacturers but will also add scientific validation. Discussions during the presentations and other personal interactions lead to one other major important observation. Field simulation of the experimental results will provide an excellent addition and compelling argument for wider adoption of the proposed protocol.

This report is presented in 3 sections. The procedure for acceptance of a new coating system by NJDOT is presented in Section I. Section II covers the details of the experimental procedure and results to be presented to NJDOT approval committee and Section III presents a procedure for predicting field service life using the accelerated test results.

OBJECTIVES

The primary objective was to update the NJDOT procedure to accept new coating systems for over-coating. The current system which is based on NEPCOAT recommendation had to be replaced with a new protocol. The new protocol had to have detailed information about conducting the accelerated corrosion tests and reporting results to NJDOT Committee. Acceptance criteria is also to be established.

A model was also to be developed to predict the service life of the coating using the accelerated test results. This information will be of immense help for planning future over-coatings.

RESEARCH WORK PLAN

The major tasks were: Update the procedure for accepting new coatings by incorporating the recently developed test protocol, develop a model to predict field service life using accelerated test data, promote the use of the new test protocol at national level and preparation a final report that will provide guidelines for industries to submit request for adding new coating systems. The results are presented in three sections.

SECTION I

PROCEDURE FOR ACCEPTANCE OF NEW OVER-COATING SYSTEMS TO BE ADDED TO QUALIFIED PRODUCTS LIST (QPL)

The following are the key steps.

1. Submission of basic information for initial review.
2. If the product satisfactory in the initial review, NJDOT will provide guidelines to submit the required test results on durability of the coating.
3. If all the requirements are met, the product will receive initial approval and be included in the QPL as provisional candidate.
4. Final approval will be given after obtaining field data for a minimum of 2 years.

Further details are provided in the following sections.

Initial Submission

The person representing the company should provide basic information about the product including: MSDS sheets, any Technical Data Sheets, Number of coats, curing details, information on the durability and field applications.

The product should be in full compliance with EPA requirements on environmental and health aspects such presence of carcinogens, lead and VOC.

Information on Durability

The product should be tested for durability. If the product was already tested using established test protocols by other transportation agencies, they can be submitted. Otherwise NJDOT will provide guidelines to conduct the tests and report results. The key parameters are:

- Corrosion growth
- Degradation of protective (top) coats in terms of change in color and thickness
- Effect of bolted and welded connections.

Criteria for acceptable values will be provided. The tests should be conducted by a certified laboratory approved by NJDOT.

Initial Approval

Details are provided in the next section.

Final Approval

Details are provided in the next section.

Additional Recommendation

It is also recommended to update Section 912.01.01 with the following statement.

912.01.01 Structural Steel Paint

Use paint systems for coating structural steel that are Northeast Protective Coating Committee (NEPCOAT) approved and listed on the QPL. Use the appropriate paint type for the application as follows:

1. Use an inorganic zinc, epoxy, urethane (IEU) paint system for coating new structural steel.
2. Use an organic zinc, epoxy, urethane (OEU) paint system, or a New Over-Coating paint system for over-coating existing structural steel.

BUREAU OF MATERIALS
MATERIALS APPROVAL PROCEDURES

MAP Number 120-21

Effective Date: April 1, 2021
Approved By: Edward Inman

PROCEDURE FOR APPROVAL OF STRUCTURAL STEEL PAINT OVER-COATING PAINT SYSTEMS

PURPOSE

To establish a procedure to approve New Over-Coating Paint Systems for addition to the NJDOT Bureau of Material's Qualified Products List (QPL).

REFERENCES

New Jersey Department of Transportation Standard Specifications for Road and Bridge Construction 2019
Section 912.01.01, Structural Steel Paint: Current procedure for structural steel paint on new steel is referenced and covered under MAP-119 which details NEPCOAT testing of IEU and OEU paint systems for acceptance criteria and possible addition to NJDOT QPL. https://www.nj.gov/transportation/eng/materials/pdf/map-119.pdf
Materials Procedure MP-44, Infrared (IR) Spectrophotometry Analysis of Structural Steel Paint
Materials Procedure MP-34, Chemical Analysis of Structural Steel
ASTM B 117, Standard Practice for Operating Salt Spray (Fog) Apparatus
ASTM D 5894, Standard Practice for Cyclic Salt/Fog UV Exposure of Painted Metal (Alternating Exposure in a Fog/Dry Cabinet and a UV/ Condensation Cabinet.
AASHTO R 31, Standard Practice for Evaluation of Coating Systems with Zinc-Rich Primers
Society for Protective Coatings SSPC – SP2, SP3
New Jersey Department of Environmental Protection, New Jersey Administrative Code (NJAC) Title 7, Chapter 27, Subchapter 23 – Prevention of Air Pollution From Architectural Coatings

PROCEDURE

A. Manufacturer's Request for Approval.

The Manufacturer shall request in writing for the approval of the paint system. Include the following information in the request:

1. The name, address, and contact information for the manufacturer.
2. Technical datasheets for the primer and finish coats used in the system.

3. VOC data for the primer and finish coats used in the system.
4. Materials Safety Data Sheet (MSDS)

Mail the request for approval and samples to the following:
Mailing Address (USPS):
Manager, Bureau of Materials (Thiokol Bldg. 4) Manager, Bureau of Materials (Thiokol Bldg. 4)
New Jersey Department of Transportation New Jersey Department of Transportation
Street Address (UPS, FedEx, etc.):
P.O. Box 600 930 Lower Ferry Road
Trenton, NJ 08625-0600 West Trenton, NJ 08628
PROCEDURE FOR APPROVAL OF STRUCTURAL STEEL PAINT –OVER-COATING PAINT SYSTEM MAP-120

B. Bureau of Materials Review of Test Data

If the system meets the VOC content limits in NJAC 7:27-23, then the ME will provide more information for durability testing of the coating system. If the data indicates that the paint system does not meet the VOC requirements, the ME will reject the paint system for approval.

C. Laboratory Testing

The test can be conducted using a procedure developed for NJDOT or tests used by NEPCOAT. The NJDOT procedure can be completed in a shorter time and more details will be provided on initial approval. In either case the tests should be conducted by a certified laboratory preapproved by NJDOT.

C 1. NJDOT Test Procedure
If NJDOT test protocol is chosen for the test detailed guidelines will be sent for testing and reporting.

For the NJDOT accelerate test the following are requirements.

- ☐ Minimum adhesion strength of virgin coating should be greater than 600 psi
- ☐ Corrosion growth predicted by the regression equation should not exceed 4mm at 100 cycles of exposure.
- ☐ Minimum adhesion strength of coating after 100 cycles of exposure should be greater than 250 psi
- ☐ Adhesion strength after 100 cycles of exposure should be greater than 30% of adhesion strength of virgin coating
- ☐ Coating should be applied using sprayer on a hand tool prepared surface of a rolled steel section
- ☐ Change in color measured using color meter or equivalent method should be less than 10%.
- ☐ Reduction in thickness should be less than 10%.
- ☐ No visible deterioration at the location of bolt holes and weld lines.

C 2. NEPCOAT acceptance criteria (as stated on NEPCOAT website) procedure
NEPCOAT procedure involves testing of panels prepared as shown in Figure MAP 120-1. Test two panels for 5000 hours of exposure to salt fog (ASTM B 117) and two panels for 5000 hours of exposure to cyclic weathering (ASTM D 5894).
For NEPCOAT procedure, the ME will evaluate the test panels after exposure according to AASHTO R 31, Section 8.2.2. If the paint system meets the criteria listed in Table MAP 120-1 and Table MAP 120-2, the ME will approve the system. If the paint system does not meet the criteria in Table MAP 120-1 and Table MAP 120-2, the ME will reject the paint system for approval.

Table MAP 120-1 Acceptance Criteria for Salt Spray (Fog) Resistance Test
(ASTM B 117)

Maximum Creep @ 5000 hours[1] (maximum) 4 mm
Maximum Creep @ 5000 hours[1] (maximum) 2 mm
Blister Conversion Value @ 5000 hours[1] (minimum)

[1] Evaluation of the specimens according to AASHTO R 31, Section 8.2.2.

Table MAP 120-2 Acceptance Criteria for Cyclic Weathering Resistance
(ASTM D 5894)

Maximum Creep @ 5000 hours[1] (maximum) 4 mm
Maximum Creep @ 5000 hours[1] (maximum) 2 mm
Blister Conversion Value @ 5000 hours1 (minimum) 6

[1] Evaluation of the specimens according to AASHTO R 31, Section 8.2.2.

If the paint system is approved, the ME will test each component of the paint system to establish a baseline and tolerance for acceptance of production run samples. The ME will establish the tolerance with the manufacturer for viscosity, weight per gallon, percent solids, percent pigment content and IR spectrophotometry.

PROJECT ACCEPTANCE REQUIREMENTS

Qualification of a product and addition to the QPL does not constitute a blanket approval of the material. The Contractor for each proposed project must submit the product and source on a Materials Questionnaire as specified in Section 106. The ME will approve the product and source on a project to project basis based on the specifications for the project. The ME will sample, test and accept the material according to the applicable Section of the NJDOT Standard Specifications for Road and Bridge Construction.

DISQUALIFICATION

The ME may remove the product from the QPL for non-conformance with specification requirements or for a documented history of poor field performance. The manufacturer shall notify the ME, in writing, of any change in product formulation. Failure to notify the ME of changes in product formulation will result in disqualification.

REQUALIFICATION

The ME will reevaluate a product which has been disqualified and removed from the QPL only after submission of a formal request along with acceptable evidence that the problems causing the disqualification have been resolved.

The ME may require the manufacturer to requalify the product for any of the following reasons:

1. To ensure that obsolete products are not kept on the list, the ME may request written confirmation from the manufacturer that the product is still available and has not changed formulation. Failure to respond to the
Bureau's written request will result in the product being removed from the list.
2. If the formulation of the product has changed, the ME may require that the new formulation be requalified.
3. If the Department's standard specifications change or if the referenced Standards change, the ME may require requalification to ensure that the product meets the new specification.

SECTION II

GUIDELINES FOR ACCELERATED DURABILITY TEST FOR COATINGS ON STRUCTURAL STEEL TO REDUCE CORROSION[1]

SCOPE

The guidelines presented in this document provides information for conducting accelerated environmental exposure tests to evaluate potential new coatings that can be used on steel surfaces of transportation infrastructures.

REFERENCE DOCUMENTS

1. ASTM G154-16, “Standard Practice for Operating Fluorescent Ultraviolet (UV) Lamp Apparatus for Exposure of Nonmetallic Materials”, ASTM International, 2016, West Conshohocken, PA.
2. ASTM Standard B117-16, “Standard Practice for Operating Salt Spray (Fog) Apparatus”, ASTM International, 2016, West Conshohocken, PA.
3. ASTM Standard D4541-17, “Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers”, ASTM International, 2017, West Conshohocken, PA.
4. 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.
5. Balaguru, P., Najm H., and Caronia, D., “Evaluation of Different Paint Systems for Over-Coating of Existing Structural Steel.” New Jersey DOT, Report No. FHWA-NJ-2018-006, August, 2018.

SIGNIFICANCE AND USE

The test protocol presented in this document can be used to evaluate a new coating system within 6 months. The time needed for accelerated environmental degradation exposure is 100 days. The laboratory test results correlates one long term field study. The test method was developed as part of a research grant from New Jersey Department of Transportation (NJDOT) to Rutgers the State University of New Jersey. The test results can be used for accepting a new coating system.

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[1] This guideline was written for acceptance testing of coatings to be used on steel surfaces for New Jersey Department of Transportation

EQUIPMENT

The equipment needed consist of an Accelerated test chamber, freezer, equipment for surface preparation, application of coating, gage for measuring thickness of coatings, color meter to measure color change and supplies including dollies for adhesion strength measurement, epoxy and rubber of plastic O rings.

Accelerated Test Chamber

Test Chamber can either be purchased or built using materials that will not corrode. If the chamber is fabricated, it should conform to all the required specifications of ASTM standards: D5894 and B117. One exception is the use of salt spray instead of fog specified in the ASTM standard. The salt spray enhances the accelerated corrosion and also simulate the corrosion caused by running salt contaminated water on the surfaces of steel structural components. An economical version built using a plastic tank is shown in Figure 1. The key elements are tank, holding rack for placing specimens built inside the tank using non-corrosive materials and all ASTM specifications such as angle of holding racks, system for spraying salt water, UV lights that also provides heat, reservoir for holding salt solution, motor for pumping and spraying the liquid, electronic control systems for automation. The holding racks should be placed parallel to the principal direction of the salt spray in the chamber and positioned so that the specimens can be held at an angle between 15° and 30° from the vertical axis. Tubes and spray nozzles made of non-corroding materials should be installed and connected to a pump with controls for running automated wetting/ drying cycles. Lamps for UV exposure and heating should be built-in and synchronized to come on during the drying cycle. The heating system should be capable of achieving and maintaining a temperature of 122 ± 5°F (50 ± 3°C) within an hour, as specified in ASTM D6944-15 guidelines. The accelerated heating system can also be used as a drying system. If properly designed in terms of power and placement, UV lights can be used to achieve all 3 functions of: drying, heating and UV radiation. The operation of salt sprayers, UV lights and heating system can be automated using timers. Movement of specimens to and from deep freezer and replenishment of the salt solution every day (one master cycle) can be done manually.

Figure 1. Chamber for Accelerated Testing: Salt Sprayers and Holding Rack

Freezer

For the deep freeze exposure, commercially available deep-freezer can be used. The freezer should have the capability to maintain a temperature of -20 ± 5°F (-29 ± 3°C) satisfying the guidelines in ASTM D6944-15. The size of the freezer should be chosen based on the number and size of the samples.

A 7.0 cubic foot compact chest freezer that can hold up to 50 small specimens is shown in Figure 2. Removable shelves can be built in for efficient utilization of the space as shown in the Figure 2.

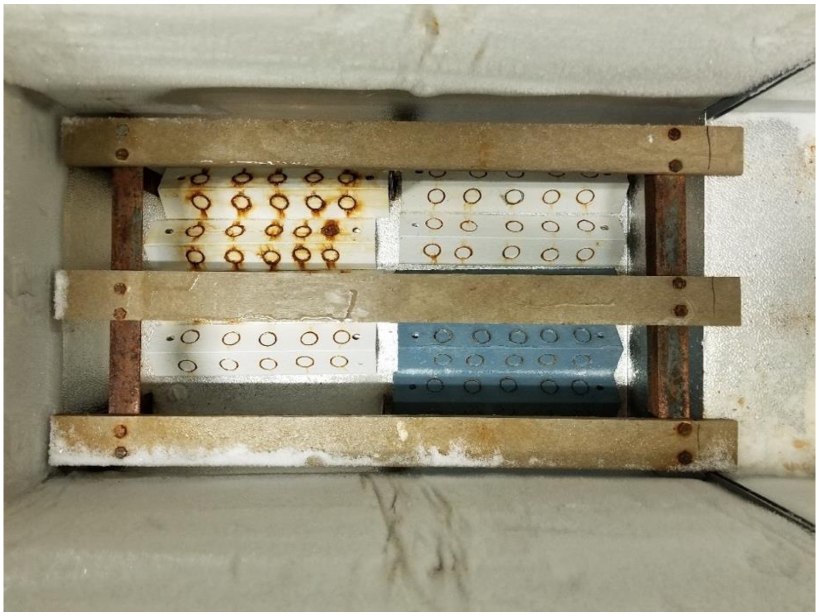


Figure 2. Freezer with Built-in Removable Shelf

Pull-off Tester

The tests should be conducted using the specification of ASTM D4541-17, Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers. To conduct this test, PosiTest® AT-M Manual Adhesion Tester, shown in Figure 3 or an equivalent tester can be used.

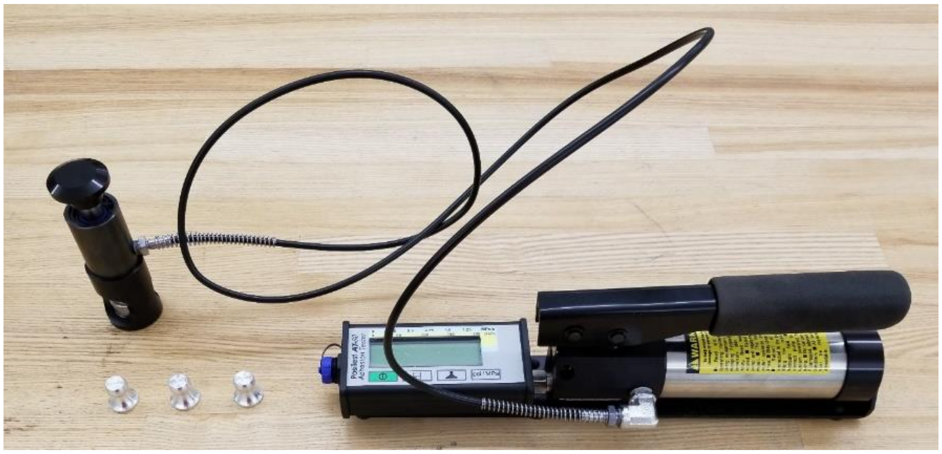


Figure 3. Pull Off Tester and 20 millimeter Pull Off Dollies

Thickness Gage

A PosiTest® DFT – dry film thickness gage shown in Figure 4 or equivalent for measuring the thickness of coatings.

Figure 4. Thickness gage used for measuring the thickness of paint layers

Color Meter

Colormeter, shown in Figure 5 or an equivalent instrument for monitoring the color change of the coatings. The Colormeter should have the capability to provide 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.

Figure 5. Konica Minolta CR-10 Plus Color Reader

Hand-held Grinder

For surface preparation, hand-held machines should be used. Hand-held grinder shown in Figure 6 or an equivalent machine can be used for light grinding.

Figure 6. Aurand hand-held steel toothed cleaning machine

Low Pressure Sprayer

The low- pressure paint systems shown in Figure 7 Earlex HV5500 Spray Station or equivalent sprayer.

Figure 7. Low Pressure Spray Apparatus

Supplies

Dollys, epoxy, O rings, water-soluble glue, rags for cleaning, de-icing salts, containers and mixers for preparing salt solutions

TEST SAMPLES

The test samples should be made of rolled steel sections and the geometry should have edges. Small size rolled steel L, T or I sections can be used for test samples. Two lines of weld at least 1 in. long should be placed and two 0.5 in. bolt holes should be drilled. A typical L section is shown in Figures 8 and 9. A minimum of 3 samples should be tested.

Figure 8. Typical ½ inch diameter holes in steel specimens

Figure 9. Typical 1-inch-long welds on steel specimens

PREPARATION OF TEST SAMPLES

The surface of the steel angle should be prepared as per the requirements of the coating manufacturer. Hand held mechanical tools should be used for surface preparation. Circular scribes should be placed on the surfaces. The scribes can be created by cutting or grinding after the coating is cured or it can be pre-placed. The following procedure can be used for pre-placing the scribes. On each face of the angles, attach O-rings using a water-soluble glue as shown in Figure 10. The O-rings should have an inner diameter of 20.6 millimeter and an outer diameter of 23.8 millimeters.

Figure 10. O-rings attached to steel specimen

Figure 11. Spray Painting Specimens

After the water-soluble glue has cured, apply the coating using a low-pressure sprayer, Figure 11. After the curing of the coating, measure the thicknesses and verify that the thickness variation satisfies both the requirements of the manufacturer and NJDOT. Remove the O-rings after the coating process is completed. The painted circle area within the scribe formed in the specimen will be the location where a 20 millimeter pull off dolly will be attached for coating-adhesion strength testing. The scribe should be 3 mm around the 20 mm diameter coating patch. Remove any residue from the water-soluble glue without damaging the coating. A typical sample is shown in Figure 12.

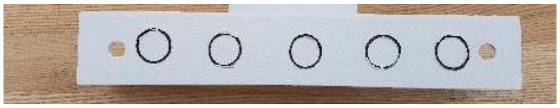


Figure 12. Painted steel specimen with O-rings removed

EXPOSURE TO ACCELERATED DEGRADATION TEST CONDITIONS

Use ASTM D5894-16 (2016) standard as a reference for the exposure scheme. The samples have to be exposed to 100 Master cycles. Each Master Cycle that lasts for 24 hours, should consist of: alternating 8 one hour wetting and one hour drying cycles for a total of 16 hours and 8 hours of deep freezing. Wetting should be done in a salt solution at 5% concentration by weight. Use the de-icing salt that is being used by NJDOT. During the drying cycle, turn on the UV bulbs. The UV bulbs can also be used to heat the samples. The 16-hour wetting, drying, UV exposure and heating can be automated. The salt solution should be replaced every day. Remove the samples after every 10 days and conduct the adhesion strength tests and inspect for any damage of coating. Conduct measurements for change in thickness and color at every 20 cycles.

MEASUREMENT OF DEGRADATION OF THE COATINGS AND CORROSION GROWTH

Record the degradation of the coating and the resulting corrosion of steel surface by measuring the adhesion strengths of the circular patch of coating, change in thickness, change in color and visually inspecting the performance at the weld lines and bolt holes. Adhesion strength reduction will provide information for quantifying corrosion-creep growth. Degradation of the top coat measured using the change in color and overall thickness of the coating will provide information for evaluating the protective coat. The weld lines and sharp edges at the bolt holes are also prime locations for initiation of damaged location. Monitor these locations by visual inspection.

Adhesion Strength Measurement

ASTM D4541, Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers (PosiTest® AT-M Manual Adhesion Tester) should be followed for measuring the adhesion strength of the 20 mm diameter coatings isolated by the scribe. The adhesion strength should be measured at least in 3 locations after every 10 master cycles of exposure. Average the 3 measurements and record the adhesive strength. The first set of adhesion strengths should be obtained right after proper curing of the coatings. After each 10 master cycles of exposure in the accelerated corrosion chamber, take out the specimens, rinse with clean water to remove any debris or residue and dry with low-pressure compressed air. After cleaning, glue three 20 mm pull off dollies to the circular painted areas within the scribe using a two-part manufacturer supplied epoxy and cure the epoxy for the required minimum of 24 hours. After the epoxy is cured, measure the adhesion strengths. A typical measurement set-up is shown in Figure 13. The tensile load should be applied at a constant rate of 1

MPa/s. This rate of loading satisfies ASTM requirement that the test should be completed within 100 seconds. After each test, record the maximum tensile stress and failure mode. Take pictures of the exposed area after pulling out the paint patch. The picture should show the corrosion growth from the perimeter towards the center of the circle. Label the pull off dollies and keep them for comparative evaluation at various stages of corrosion. Once testing is completed, place the specimens in the test-chamber for further exposure. Conduct the final pull off test after 100 master cycles of exposure.

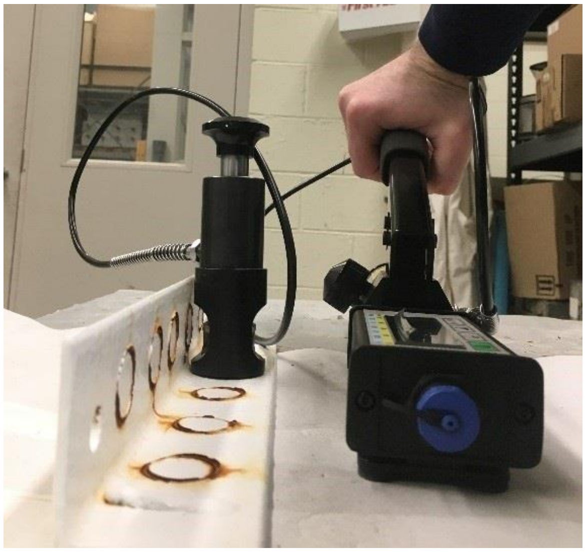


Figure 13. Adhesion strength test

Thickness Change Measurement

Measure the thicknesses of the coatings at 9 random locations after every 20 master cycles exposure using a thickness measuring gage, Figure 4. Record the average thickness.

Color Change Measurement

Using Color meter measure the color change at 9 random locations after every 20 master cycles of exposure, Figure 5. The Color meter provides three readings designated as a*, b*, and L* coordinates. Record all three values. Clean samples to remove the rust spots before taking the Color meter readings

Visual Inspection

Visually inspect the samples after every 10 master cycles to identify any changes in color, peeling of coatings or any other anomalies. Particular emphasis should be given for locations at the edges of bolt holes and around weld lines.

REPORT

The report should consist of details about the Test Specimens, key parameters of the test set-up including pictures, adhesion strength variation during the accelerated environment conditions, pictures of condition of steel surface after removal of coatings, change in thickness, change in color and any visually observed defects. Specific information that should be reported are presented in sections 9.2 to 9.5. A model report is presented in Appendix B for reference.

Details of Test Specimens and Test Set-up

Type of steel, geometry and dimensions.
Location of bolt holes and weld lines with a picture.
Picture of Test Set-up showing the entire arrangement and location of racks and UV bulbs.

Adhesion Strength

Numerical values of adhesion strength at every 10 cycles of exposure.
A graph that shows the decrease of adhesion strength.
Pictures of steel surface after pulling out the coating patch at 3 locations, for every 10 cycles of exposure.

Thickness Change

Average thickness at every 20 cycles of exposure.
A graph that shows the variation of thickness during the entire test.

Color Change

Average color, the coordinate L* at every 20 cycles of exposure.
A graph that shows the variation of color during the entire test.

Visual Inspection

Condition of the sample with particular reference to bolt holes and weld lines during the entire test duration.

APPENDIX A

DETAILED INFORMATION FOR BUILDING THE TEST CHAMBER

The test chamber consists of a corrosion resistant tank in which the samples are exposed to cyclic, wetting and drying, UV and heat. Details for building the set-up are presented in the following sections. Deep freezing can be done in a commercially available freezer.

A1. Tank with Sprayers and UV Lights Arrangement

The Chamber consisted of a 5/16-in. thick, 150-gallon polyethylene plastic tub(tank) with a drain at the bottom center of the tank. A polyethylene tube was used to connect the tub to a 10-gallon salt solution reservoir as shown in Figure A1. A 120/240V AC, 1/3 HP Stainless Steel Circulation Pump was used for pumping the salt water to the nozzles. A pump designed for caustic fluids was chosen to ensure that the salt water solution does not corrode the internal elements of the pump and potentially risk pump failure. The pump was connected to the salt solution reservoir by a cam and groove connection as shown in Figure A2, to allow easy removal of the salt water storage tank for maintenance.

Figure A1. Polyethylene Plastic Tub with a Capacity of 150 Gallon and Salt Water Solution Reservoir

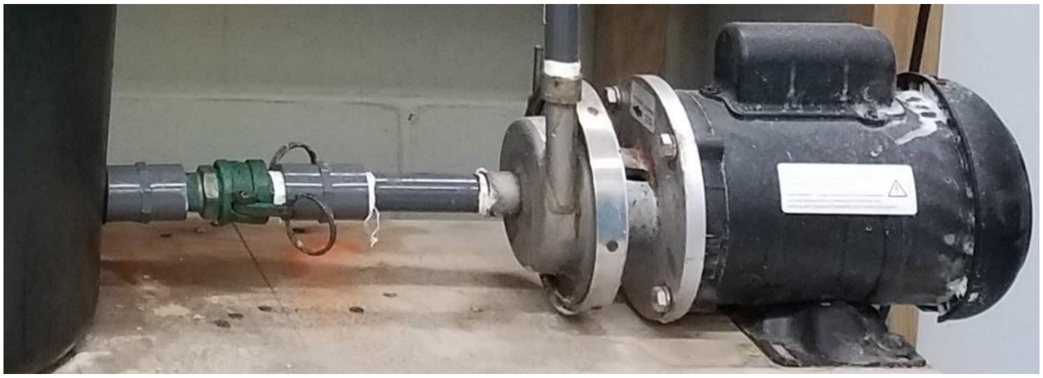


Figure A2. Salt Water Solution Reservoir Connection to the Pump

To the outlet of the pump, a ½ in. inner diameter high pressure PVC clear tubing that reduces to a ¼ in. (inner diameter high pressure PVC clear tubing) for connecting nozzles, was connected. The high-pressure PVC tubing was selected to reduce the risk of potential tube rupture from the pumping pressure. Along the top edge of the tub 10 flat spray nozzles were attached. An additional, 4 spray nozzles were attached at the lower edge of the tank. This arrangement provided an even salt spray coverage of the specimens in the chamber as shown in Figure A3.

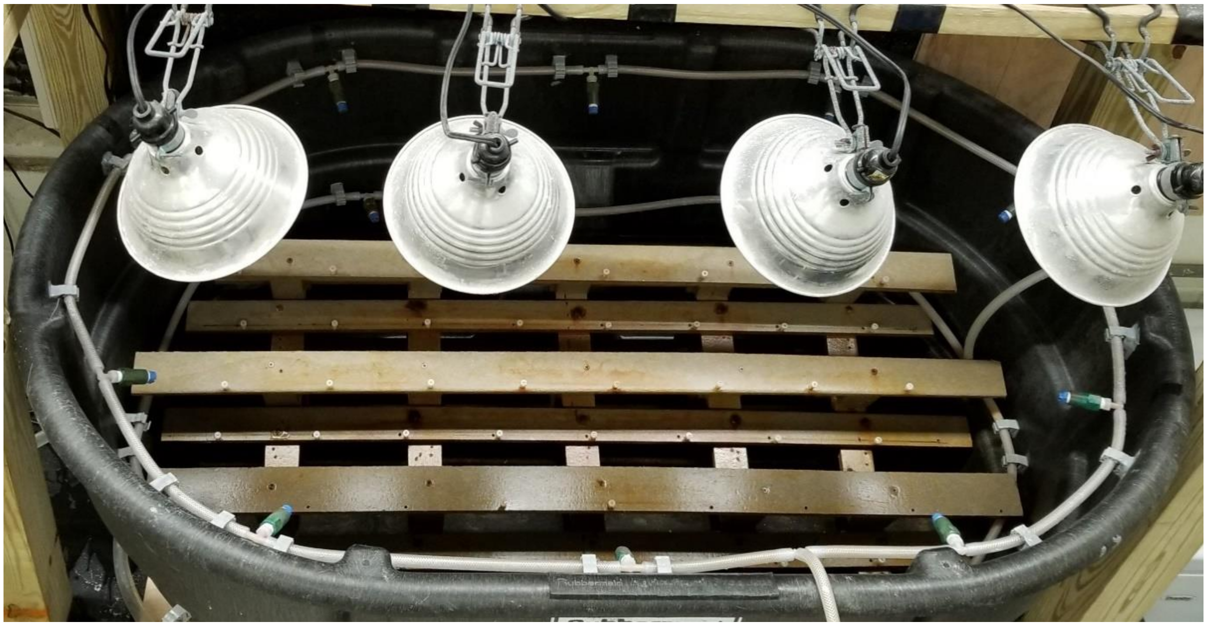


Figure A3. Salt Sprayer Layout

The flat spray nozzles were made out of polyvinylidene fluoride (PVDF), and had a ¼ in. NPT male threads as shown in Figure A4. These flat spray nozzles were connected into ¼ inch NPT bronze adapters which in turn connected to a nylon inline tee adapter as shown in Figure A5.

Figure A4. PVDF Flat Spray Nozzles

Figure A5. Salt-Water Sprayer Assembly

Adjustable clamping hangers were epoxied to the tank walls to hold the PVC tubes in place. As the salt water is sprayed, the water drips off of the specimens, and then flows back into the salt solution reservoir for recirculation. To automate the spraying system, the pump was connected to a time activated on/off switch that operates seven days a week. The on/off switch was programmed for 1 hour on/ 1 hour off. This on/off cycle ran between 5 pm and 9am, resulting in a total of 8 cycles of 1 hours of salt-water wetting by sprayers and 1 hour drying.

A2. Rack for Placing Specimens

The specimen holding rack was constructed to ensure uniform: salt-water spray application, infrared heat and UV exposure to each specimen. To prevent deterioration from the salt water, heat and UV exposure, the rack was constructed using high density polyethylene (HDPE) synthetic wood and galvanized wood screws. The racks were placed at two levels, each at an angle of 17 degrees as shown in Figure A6. This angle resulted in evenly coated samples without excess salt-water collecting on the surface of samples. The maximum possible size was chosen to optimize the space inside the chamber.

Figure A6. Specimen Holding Rack

To reduce the effects of sagging and relaxation of the HDPE synthetic wood from creep, the elements on the holding rack were doubly reinforced. In addition, at every four inches along the support beams where the specimens were to be placed, a ¼ in. diameter, ½ in. long nylon shoulder screws were installed. The specimens were placed at these locations to prevent slipping of samples as shown in Figure A7. The nylon shoulder screws were selected due to their chemical resistant, non-conductive, and light weight properties.

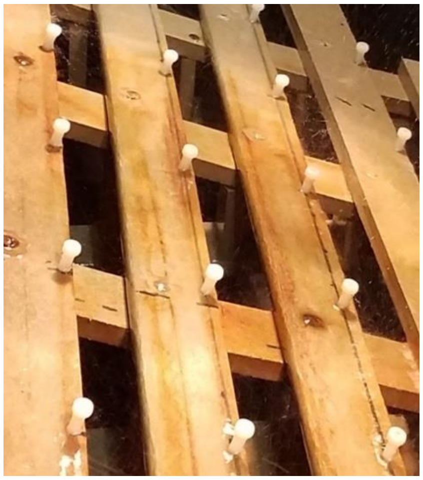


Figure A7. Shoulder Screws Installed on the Specimen Holding Rack to Prevent Slipping

A3. Heat and UV Exposure System

UV light bulbs were used for UV radiation with simultaneous drying and heating to 120 degrees Fahrenheit. To reach the required temperature, three 5-in. diameter infrared light bulbs were selected. The UV exposure requirements were met by using two A19 UV light, 120 volts 60 Hz 365 nanometer wave-length bulbs. To position the heat and UV sources directly over the specimens, a frame was constructed using pressure treated lumber. Pressure treated lumber was chosen to prevent damage due to water. The arrangement of the frame is shown in Figure A8.

Figure A8. Infrared and UV Light Frame

The frame consisted of columns that were 4 in. x 4 in. posts and cross beams that were 2 in. x 4 in. studs, arranged to fit over the 150-gallon polyethylene plastic tub, and rest on the table supporting the tub. Galvanized wood screws were used to build the frame to prevent deterioration due to corrosion. The height and location of infrared and UV lights were chosen to ensure that the required infrared heat and UV exposure are met but the bulbs will not get wet due to salt spray. The lights were set at a height of 14 in. above the tub. The infrared heat and UV lights were connected to a time activated on/off switch for automation and synchronized with the pump operation.

A4. Preparation of Salt Water Solution

The salt-water solution was prepared using de-icing salt obtained from New Jersey Department of Transportation. The salinity content was 5 percent by weight. To ensure that the de-icing road salt is mixed uniformly and can flow thru the pump freely, the salt was ground to a fine powder of approximately 1180-micron size particles using a high-speed blender. Buckets were filled with water and weighed on a calibrated scale. The required amount of salt was added to the water and mixed with a paddle mixer. The paddle mixer was connected to a power drill and mixing was done at 1500 rpm for a minimum of 90 seconds to ensure complete dissolution of salt. If salt particles resting on the bottom of the bucket were found, the solution was agitated again till all the salt is dissolved. The prepared salt-water solution was then poured into the salt solution reservoir. The salt water was replaced every day or completion of one master cycle. The reservoir was also cleaned of any debris consisting of rust particles every day.

APPENDIX B
GUIDELINES FOR PREPARING REPORT

REPORT

The report should provide details on: Test Specimens, test set-up, adhesion strength variation during the accelerated environment conditions, pictures of condition of steel surface after removal of coatings by dollies, change in thickness, change in color and any visually observed defects. A model report is presented in the following sections.

Details of Test Specimens and Test Set-up

Type of steel: Rolled mild steel.
Geometry and dimensions: 2 in. X 2 in. X 12 in. long.
Location of bot holes and weld lines: Two ½ inch diameter holes were drilled thru one leg of the angle, and 1-inch long line welds were on the other leg, Figures B1 and B2. The surface of the steel angle was prepared to satisfy the paint manufacturers required surface preparation specification. An Aurand hand held steel toothed cleaning machine was used for surface preparation.

Figure B1. Typical ½ inch diameter holes in steel specimens

Figure B2. Typical 1-inch-long welds on steel specimens

Test Set-up: 75-gallon plastic tank that can hold up to 100 samples as shown in Figure B3.

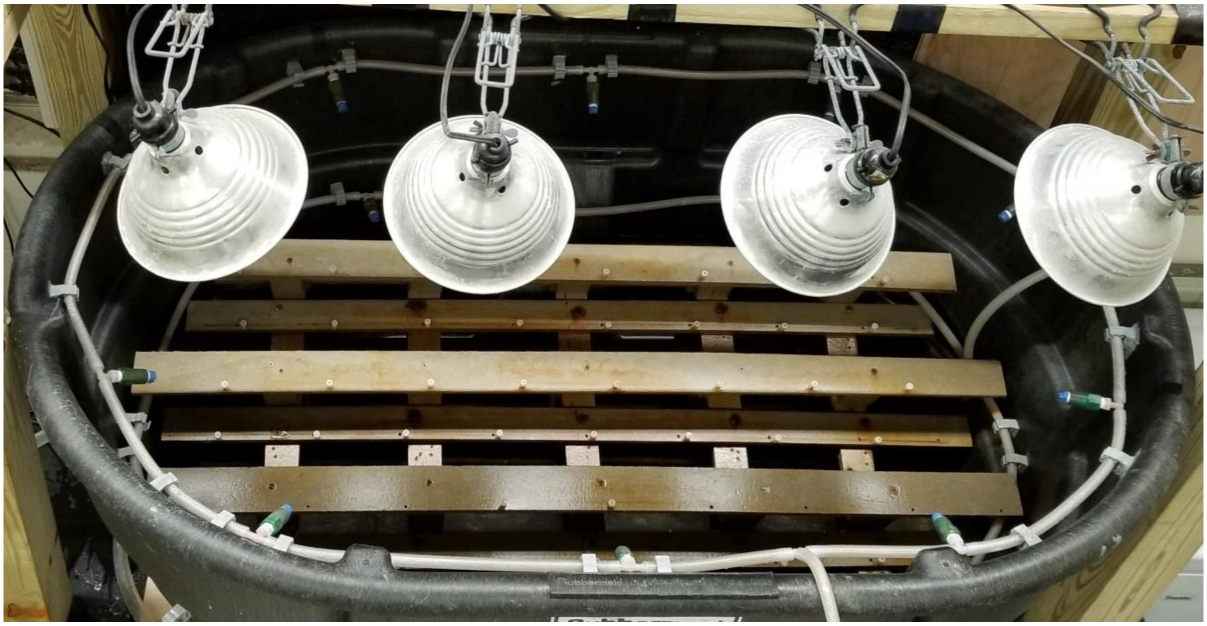


Figure B3. Test Set-up

Adhesion Strength

Adhesion strength of the coating at every 14, from 0 to 100 master cycles are presented in Table B1. Variation of strength with respect to number of master cycles is shown in Figure B4. In the actual report the results should be presented for every 10 cycles.

Table B1 - Adhesion strengths of coating from 0 to 100 cycles

Number of Cycles	Adhesion Strength (psi)
0	780
10	705
20	640
30	570
40	498
50	400
60	345
70	320
80	300
90	295
100	290

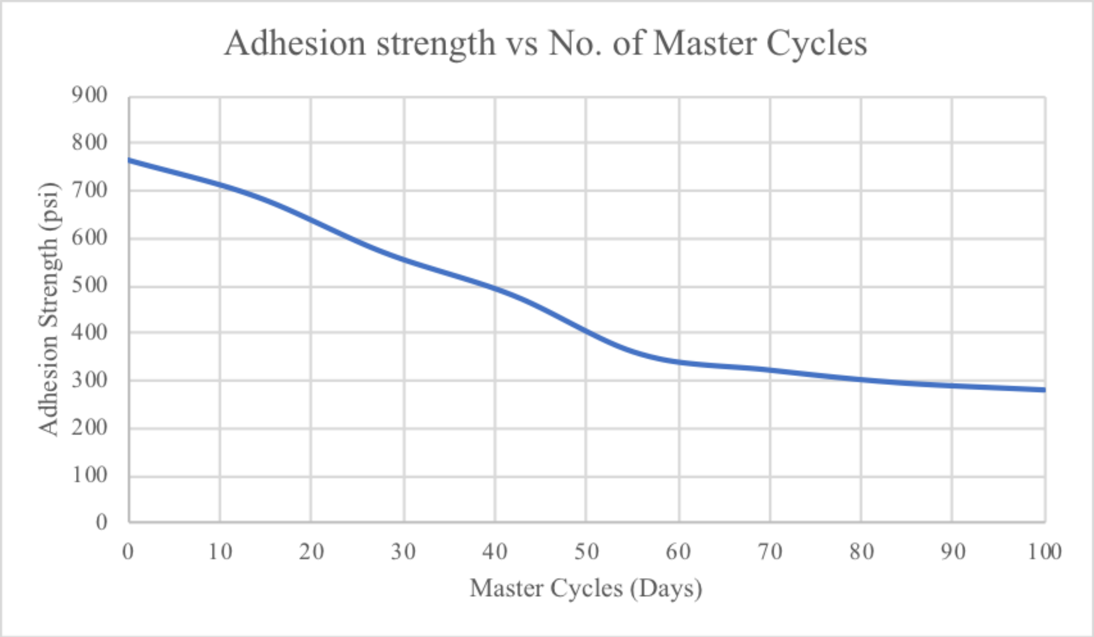


Figure B4. Adhesion Strength versus Master Cycles

Pictures of steel surface after pulling out the coating patch at 2 locations are shown for every 14 cycles are shown up to 100 cycles in Figures B5 and B6. In the actual report 3 locations for every 10 cycles should be shown up to 100 cycles.

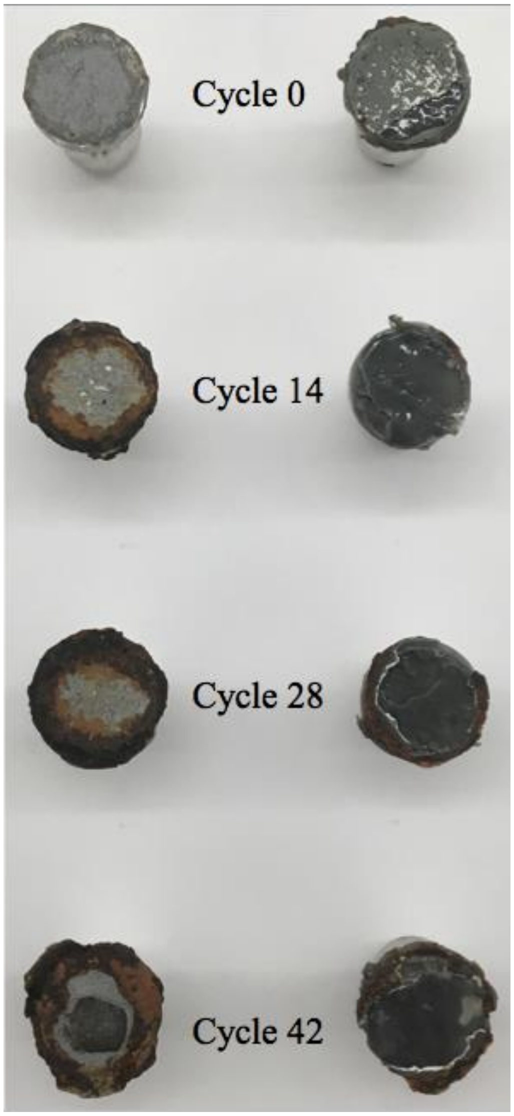


Figure B5. Steel Surface Images after Dollies are Pulled Out: Locations 1 and 2, Cycle 0 to Cycle 42

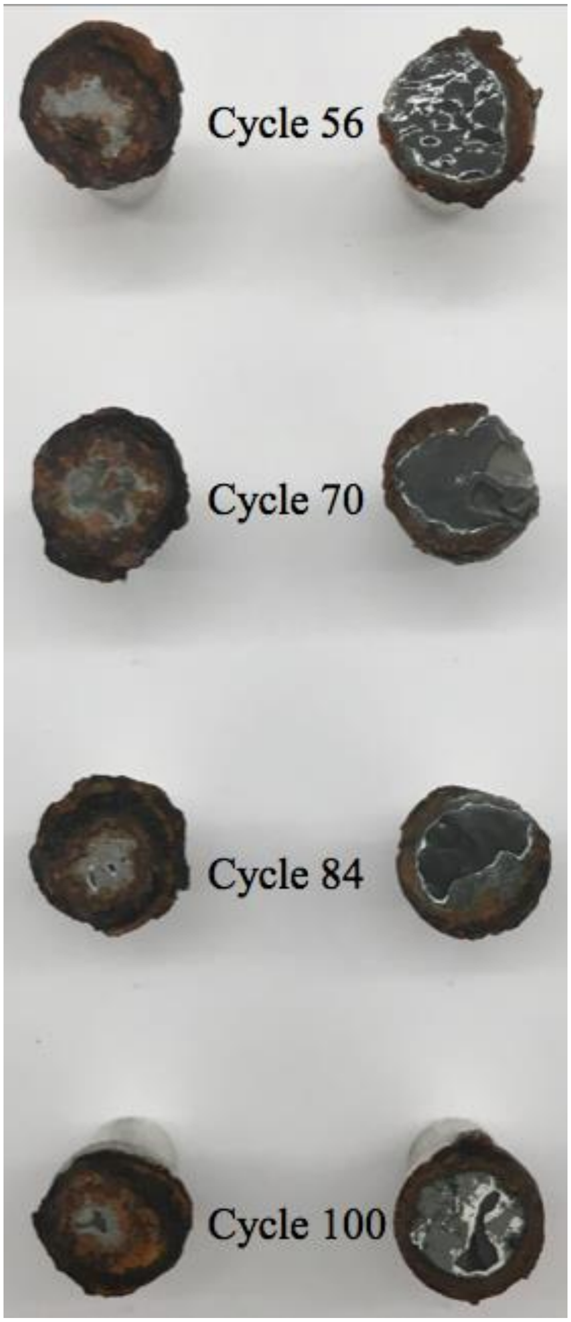


Figure B6. Steel Surface Images after Dollies are Pulled Out: Locations 1 and 2, Cycle 56 to Cycle 100

Thickness Change

Average thickness at every 20 cycles of exposure and a graph are presented in Table B2, B3 and Figure B7. Only Table B3 needs to be reported. Table B2 was added to this guideline to show the typical variation of thicknesses of multiple coat systems.

Table B2 - Thickness Readings: Individual readings

		Thin Coating System 4									
		Cycle 0 (Virgin Specimen)					**Cycle 100**				
	Recording (microns):	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
Sample 1	**Leg 1**	299	351	277	300	294	345	294	353	375	326
	Leg 2	360	315	300	324	360	285	333	278	281	333
	Leg 3	286	372	292	330	304	300	363	278	271	340
	Leg 4	303	291	297	322	351	310	339	337	302	319
Sample 2	**Leg 1**	316	296	369	288	318	290	376	339	332	318
	Leg 2	343	303	272	368	293	278	282	350	361	330
	Leg 3	322	313	340	372	341	320	330	330	282	311
	Leg 4	318	352	277	371	315	316	337	311	256	315
Sample 3	**Leg 1**	329	341	327	311	294	365	277	278	345	276
	Leg 2	333	330	336	373	327	289	313	244	286	279
	Leg 3	304	322	360	297	303	280	288	376	360	347
	Leg 4	395	340	345	309	288	375	324	284	351	393
Sample 4	**Leg 1**	298	325	292	370	328	285	317	360	341	309
	Leg 2	316	288	307	367	339	346	343	333	369	295
	Leg 3	280	343	266	301	330	278	363	363	295	282
	Leg 4	324	373	296	353	348	359	350	306	348	315
Sample 5	**Leg 1**	323	324	351	344	324	296	301	292	330	347
	Leg 2	359	358	336	365	291	366	308	331	333	350
	Leg 3	321	300	365	314	404	288	323	298	303	298
	Leg 4	295	339	304	336	288	370	301	364	308	304
Sample 6	**Leg 1**	260	288	290	321	363	369	357	342	336	316
	Leg 2	359	306	292	398	424	311	355	304	322	278
	Leg 3	306	364	303	289	301	354	348	306	280	279
	Leg 4	374	334	351	367	331	339	335	346	276	277
					Avg.	326				**Avg.**	320
					S.D.	32				**S.D.**	32

Table B3 - Thickness Readings: Average Values

Cycle Number	Thickness, microns
0	341
20	336
40	333
60	334
80	319
100	318

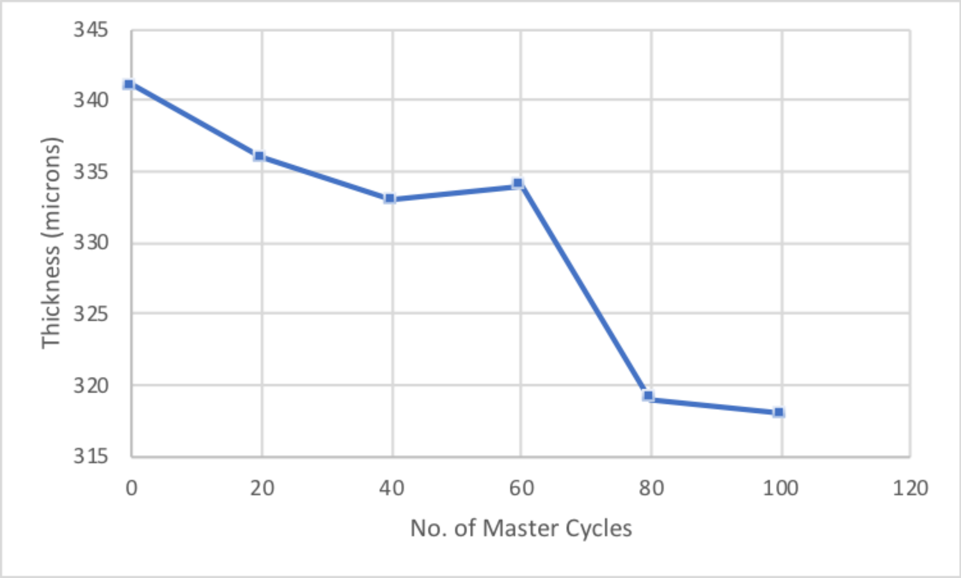


Figure B7. Change of Thickness Versus Number of Master Cycles

Color Change

Average color change at every 20 cycles of exposure and a graph are presented in Table B4 and Figure B8.

Table B4 - Color Recordings

Cycle	L*
0	95.4
20	95.3
40	93.6
60	95.3
80	95.5
100	95.7

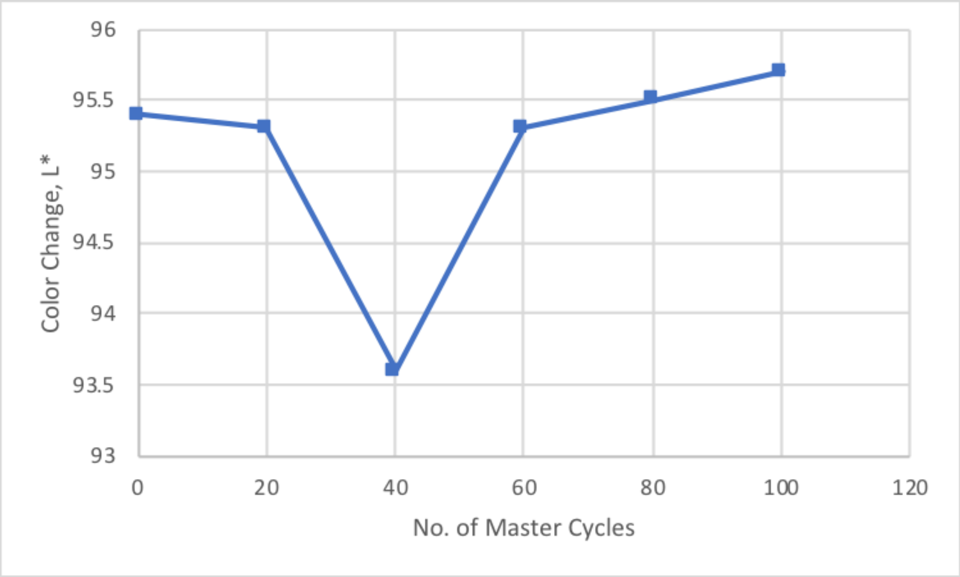


Figure B8. Change of Color Versus Number of Master Cycles

Visual Inspection

There was deterioration near the bolt holes and near the weld. Condition of the sample at various cycles of exposure are shown in Table B5 and Figure B9.

Table B5 - Visual Inspection Results

Coating System Deterioration		
Specimen	**Location of Deterioration**	**Cycle of Deterioration**
1	Weld	42
2	Weld	42
3	Weld	42
4	Hole	42
5	Hole, Weld	42
6	None	None

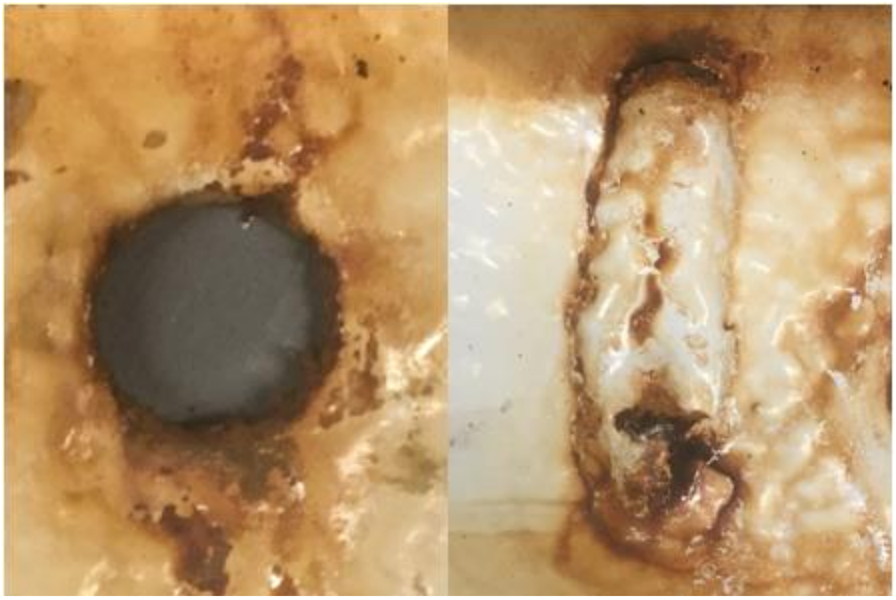


Figure B9. Typical Corrosion Pitting at Simulated Bolt Hole & Weld

SECTION III

SERVICE LIFE ESTIMATION OF COATINGS APPLIED ON STEEL SURFACES

ABSTRACT

A model for predicting the service life of coatings based on the accelerated test results is presented for steel surfaces. The primary focus is the performance of coatings applied on structural components of Transportation Structures with particular emphasis on Bridge Structures. The methodology is based on the science of corrosion, models available in existing literature, information available on field performance and results of accelerated test results. In the area of corrosion science, based on the extensive search of existing literature, the dominant variable for estimating the durability of coatings is corrosion growth from a coating-damaged location. Deterioration of intermediate and top coats that are applied to protect the prime coat also plays a role. However effective formulations have been developed for these coats for protection against harsh weathering conditions such as freeze-thaw, salt intrusion and damage due to UV radiation. The prime coat is the weakest link that determines the useful life of the coating. The model can be used to estimate the service life new formulations using accelerated test results that can be completed within one year.

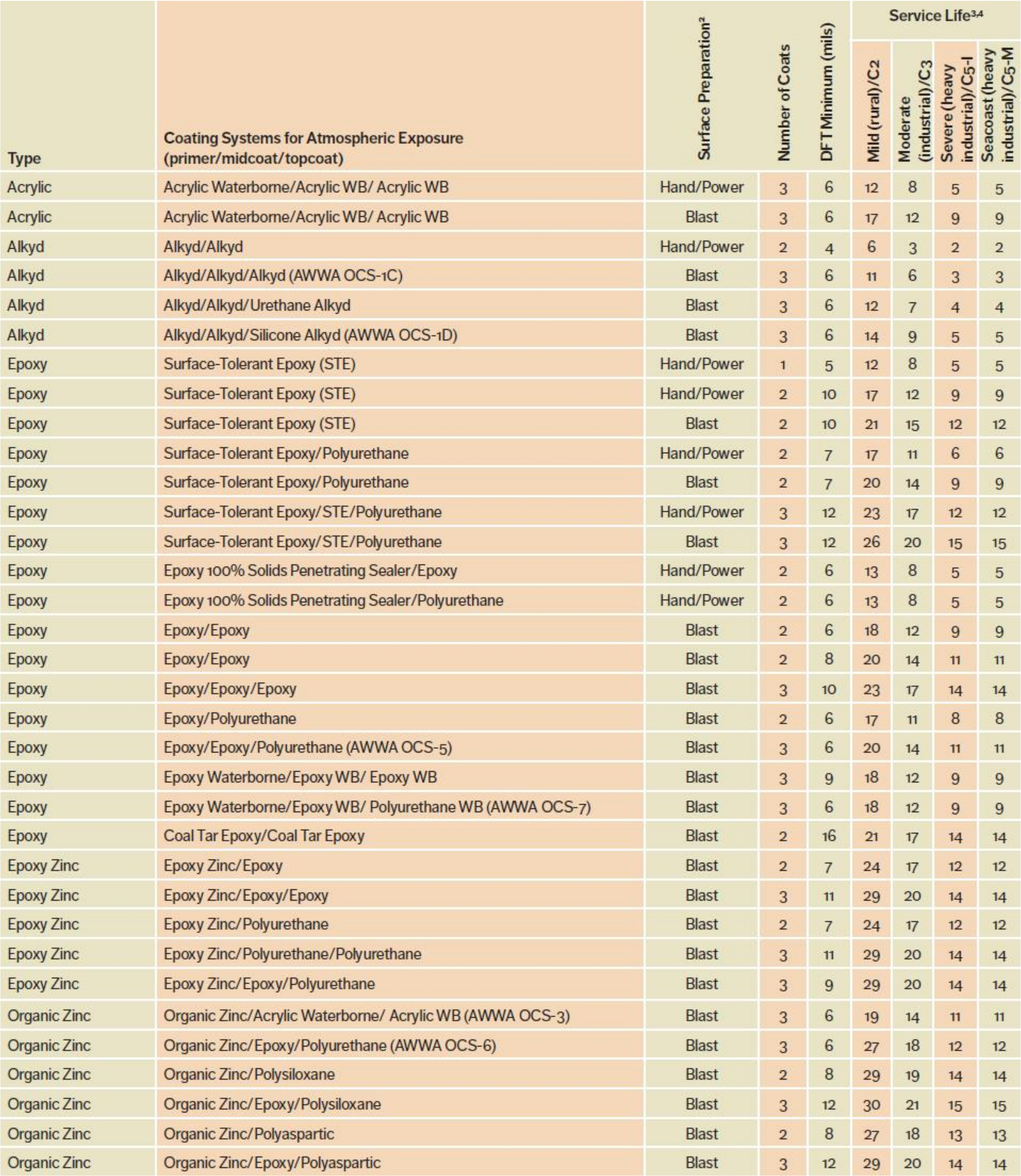
STATE OF THE ART

Currently, estimated service lives of popular coatings are available for different exposure conditions. The papers published by Helsel (21) provide an extensive list of coatings and are updated periodically. These results that can be used only for existing coatings, were used to develop the current model that can predict the service life of new coating systems based on accelerated test results. The results from Helsel (21) are presented in Table 1. The following key observations were used to develop the service life prediction model.

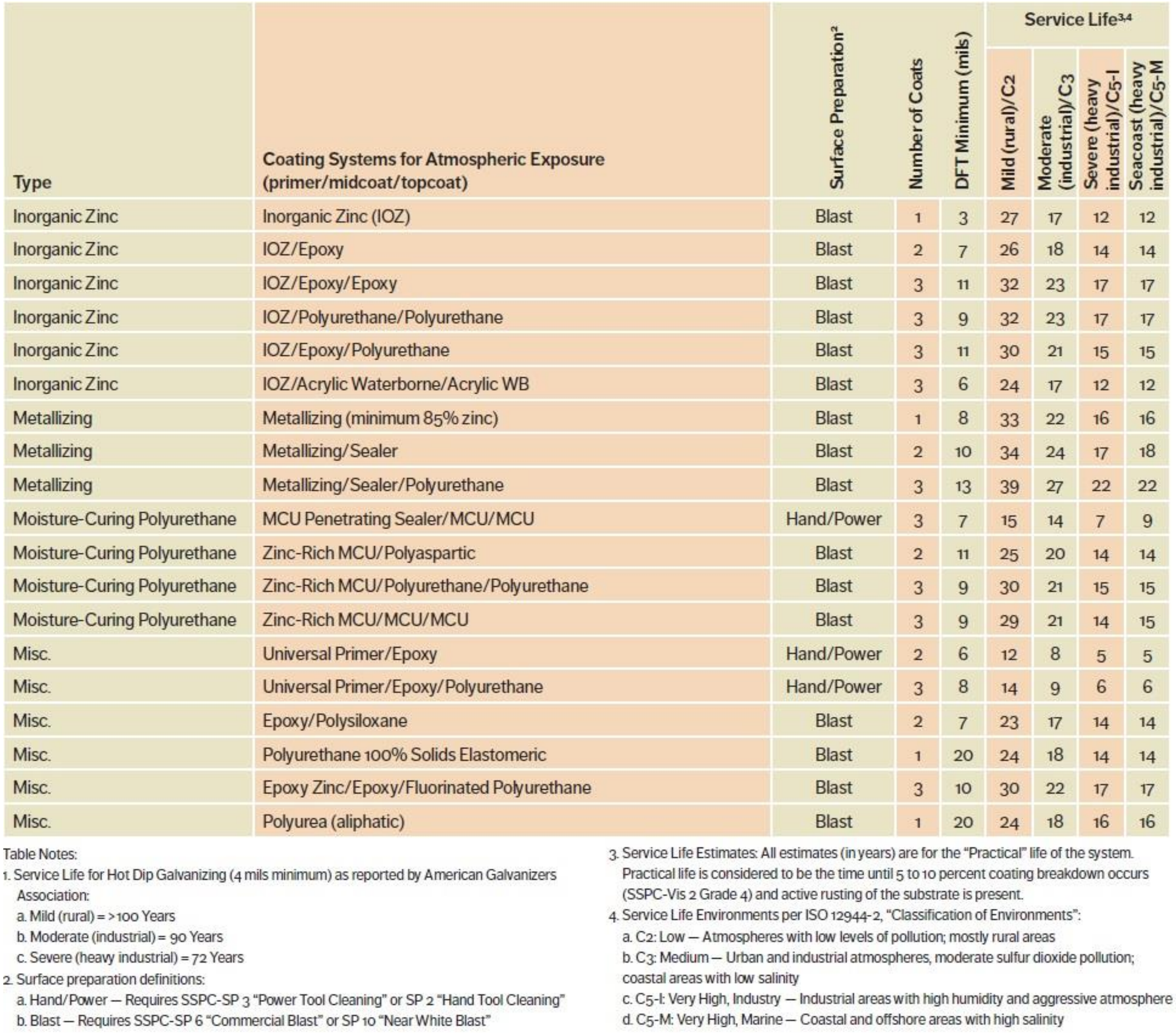
- Metalizing systems provide the best performance. The primary drawback is the high cost and complexities of application, particularly for over-coating. Therefore, these types of coatings are not incorporated in the model.
- Zinc based primers provide the second-best option. For severe or seacoast exposure, organic and inorganic zinc primer-based coatings provide comparable results. However, inorganic zinc primer provides relatively better performance than the organic primer. The service life of these coatings for harsh exposure vary from 11 to 15 years for organic zinc primer-based coatings and 12 to 17 years for inorganic zinc primers.
- Variation of service life among zinc primer-based coatings can be attributed to different types of protective layers or top-coats.
- Exposure conditions and surface preparations are two major influencing factors that determine the service life of coatings.

- Multi-layer coatings, especially 3 layer-coating systems, generally provide longer life spans.
- Useful life span of currently available coating ranges from 2 (for severe exposure) to 32 years (mild exposure).
- As expected, harsh (severe) exposure conditions result in significant reduction of service lives.
- Severe exposure conditions have a strong correlation with seacoast exposure.
- Service life can vary by as much as 15 years depending on the exposure conditions. The service life increase under mild exposure conditions for zinc primer-based coatings is more significant as compared to other primers.
- As expected, blast surface preparation provides better results as compared to hand/power tool surface preparation.

Table 1 - Estimated Service Life for Practical Maintenance Coating Systems for Atmospheric Exposure (in years before first maintenance painting), (Reproduced from: Helsel (21))



Type	Coating Systems for Atmospheric Exposure (primer/midcoat/topcoat)	Surface Preparation^2	Number of Coats	DFT Minimum (mils)	Service Life^{3,4}			
					Mild (rural)/C2	Moderate (industrial)/C3	Severe (heavy industrial)/C5-I	Seacoast (heavy industrial)/C5-M
Acrylic	Acrylic Waterborne/Acrylic WB/ Acrylic WB	Hand/Power	3	6	12	8	5	5
Acrylic	Acrylic Waterborne/Acrylic WB/ Acrylic WB	Blast	3	6	17	12	9	9
Alkyd	Alkyd/Alkyd	Hand/Power	2	4	6	3	2	2
Alkyd	Alkyd/Alkyd/Alkyd (AWWA OCS-1C)	Blast	3	6	11	6	3	3
Alkyd	Alkyd/Alkyd/Urethane Alkyd	Blast	3	6	12	7	4	4
Alkyd	Alkyd/Alkyd/Silicone Alkyd (AWWA OCS-1D)	Blast	3	6	14	9	5	5
Epoxy	Surface-Tolerant Epoxy (STE)	Hand/Power	1	5	12	8	5	5
Epoxy	Surface-Tolerant Epoxy (STE)	Hand/Power	2	10	17	12	9	9
Epoxy	Surface-Tolerant Epoxy (STE)	Blast	2	10	21	15	12	12
Epoxy	Surface-Tolerant Epoxy/Polyurethane	Hand/Power	2	7	17	11	6	6
Epoxy	Surface-Tolerant Epoxy/Polyurethane	Blast	2	7	20	14	9	9
Epoxy	Surface-Tolerant Epoxy/STE/Polyurethane	Hand/Power	3	12	23	17	12	12
Epoxy	Surface-Tolerant Epoxy/STE/Polyurethane	Blast	3	12	26	20	15	15
Epoxy	Epoxy 100% Solids Penetrating Sealer/Epoxy	Hand/Power	2	6	13	8	5	5
Epoxy	Epoxy 100% Solids Penetrating Sealer/Polyurethane	Hand/Power	2	6	13	8	5	5
Epoxy	Epoxy/Epoxy	Blast	2	6	18	12	9	9
Epoxy	Epoxy/Epoxy	Blast	2	8	20	14	11	11
Epoxy	Epoxy/Epoxy/Epoxy	Blast	3	10	23	17	14	14
Epoxy	Epoxy/Polyurethane	Blast	2	6	17	11	8	8
Epoxy	Epoxy/Epoxy/Polyurethane (AWWA OCS-5)	Blast	3	6	20	14	11	11
Epoxy	Epoxy Waterborne/Epoxy WB/ Epoxy WB	Blast	3	9	18	12	9	9
Epoxy	Epoxy Waterborne/Epoxy WB/ Polyurethane WB (AWWA OCS-7)	Blast	3	6	18	12	9	9
Epoxy	Coal Tar Epoxy/Coal Tar Epoxy	Blast	2	16	21	17	14	14
Epoxy Zinc	Epoxy Zinc/Epoxy	Blast	2	7	24	17	12	12
Epoxy Zinc	Epoxy Zinc/Epoxy/Epoxy	Blast	3	11	29	20	14	14
Epoxy Zinc	Epoxy Zinc/Polyurethane	Blast	2	7	24	17	12	12
Epoxy Zinc	Epoxy Zinc/Polyurethane/Polyurethane	Blast	3	11	29	20	14	14
Epoxy Zinc	Epoxy Zinc/Epoxy/Polyurethane	Blast	3	9	29	20	14	14
Organic Zinc	Organic Zinc/Acrylic Waterborne/ Acrylic WB (AWWA OCS-3)	Blast	3	6	19	14	11	11
Organic Zinc	Organic Zinc/Epoxy/Polyurethane (AWWA OCS-6)	Blast	3	6	27	18	12	12
Organic Zinc	Organic Zinc/Polysiloxane	Blast	2	8	29	19	14	14
Organic Zinc	Organic Zinc/Epoxy/Polysiloxane	Blast	3	12	30	21	15	15
Organic Zinc	Organic Zinc/Polyaspartic	Blast	2	8	27	18	13	13
Organic Zinc	Organic Zinc/Epoxy/Polyaspartic	Blast	3	12	29	20	14	14



Type	Coating Systems for Atmospheric Exposure (primer/midcoat/topcoat)	Surface Preparation[2]	Number of Coats	DFT Minimum (mils)	Service Life[3,4]			
					Mild (rural)/C2	Moderate (industrial)/C3	Severe (heavy industrial)/C5-I	Seacoast (heavy industrial)/C5-M
Inorganic Zinc	Inorganic Zinc (IOZ)	Blast	1	3	27	17	12	12
Inorganic Zinc	IOZ/Epoxy	Blast	2	7	26	18	14	14
Inorganic Zinc	IOZ/Epoxy/Epoxy	Blast	3	11	32	23	17	17
Inorganic Zinc	IOZ/Polyurethane/Polyurethane	Blast	3	9	32	23	17	17
Inorganic Zinc	IOZ/Epoxy/Polyurethane	Blast	3	11	30	21	15	15
Inorganic Zinc	IOZ/Acrylic Waterborne/Acrylic WB	Blast	3	6	24	17	12	12
Metallizing	Metallizing (minimum 85% zinc)	Blast	1	8	33	22	16	16
Metallizing	Metallizing/Sealer	Blast	2	10	34	24	17	18
Metallizing	Metallizing/Sealer/Polyurethane	Blast	3	13	39	27	22	22
Moisture-Curing Polyurethane	MCU Penetrating Sealer/MCU/MCU	Hand/Power	3	7	15	14	7	9
Moisture-Curing Polyurethane	Zinc-Rich MCU/Polyaspartic	Blast	2	11	25	20	14	14
Moisture-Curing Polyurethane	Zinc-Rich MCU/Polyurethane/Polyurethane	Blast	3	9	30	21	15	15
Moisture-Curing Polyurethane	Zinc-Rich MCU/MCU/MCU	Blast	3	9	29	21	14	15
Misc.	Universal Primer/Epoxy	Hand/Power	2	6	12	8	5	5
Misc.	Universal Primer/Epoxy/Polyurethane	Hand/Power	3	8	14	9	6	6
Misc.	Epoxy/Polysiloxane	Blast	2	7	23	17	14	14
Misc.	Polyurethane 100% Solids Elastomeric	Blast	1	20	24	18	14	14
Misc.	Epoxy Zinc/Epoxy/Fluorinated Polyurethane	Blast	3	10	30	22	17	17
Misc.	Polyurea (aliphatic)	Blast	1	20	24	18	16	16

Table Notes:

1. Service Life for Hot Dip Galvanizing (4 mils minimum) as reported by American Galvanizers Association:
   a. Mild (rural) = >100 Years
   b. Moderate (industrial) = 90 Years
   c. Severe (heavy industrial) = 72 Years
2. Surface preparation definitions:
   a. Hand/Power — Requires SSPC-SP 3 "Power Tool Cleaning" or SP 2 "Hand Tool Cleaning"
   b. Blast — Requires SSPC-SP 6 "Commercial Blast" or SP 10 "Near White Blast"
3. Service Life Estimates: All estimates (in years) are for the "Practical" life of the system. Practical life is considered to be the time until 5 to 10 percent coating breakdown occurs (SSPC-Vis 2 Grade 4) and active rusting of the substrate is present.
4. Service Life Environments per ISO 12944-2, "Classification of Environments":
   a. C2: Low — Atmospheres with low levels of pollution; mostly rural areas
   b. C3: Medium — Urban and industrial atmospheres, moderate sulfur dioxide pollution; coastal areas with low salinity
   c. C5-I: Very High, Industry — Industrial areas with high humidity and aggressive atmosphere
   d. C5-M: Very High, Marine — Coastal and offshore areas with high salinity

State of the Art: Summary of Field Evaluation Results of 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. Only one more investigation conducted for Missouri DOT, Meyers (31), provides some information on long-term performance of structural steel coatings. A few studies were conducted by Federal Highway Administration (FHWA) (12-20), Connecticut DOT (6), Virginia DOT (40), but the length of field exposure was limited to 5 years. This duration is very short as compared to a life expectancy of about 25 years for a good coating system. Other studies done by U.S Navy (9) 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 (33) study, several 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, vinyl, urethanes, oil-alkyds and mastics. The details of the 47 coating systems grouped into 8 generic categories are presented in Table 2. This table which was reproduced verbatim from Mathis Bridge Study (33) 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 2 - Summary of Test Coating Systems used for NJDOT Study (33)

Span	**Coating System**	**Surface Preparation Application Date**	
	Alkyd Systems (6)		
7E	Alkyd Oil Base/Si Alkyd	SP-2	Nov. 86
11E	Alkyd/Epoxy/Urethane	SP-2	Oct. 86
21W	Alkyd/Epoxy/Urethane	SP-6	Aug. 87
43W	Oil -Alkyd	SP-6	Oct. 87
13W	Oil Alkyd-3 Cts	SP-2	June 87
31W	Oil-Alkyd	SP-6	Oct. 87
	Aluminum Systems (8)		
41W	Alum. Urethane/Acryl.	SP-6	Sep. 87
12E	Alum. Epoxy/Urethane	SP-7	Oct. 86
9E	Alum. Epoxy/Urethane	SP-2/3	Nov. 86
8E	Alum. Epoxy/Urethane	SP-2	Nov. 86
6E	Alum. Epoxy/Urethane	SP-2	April 87
5W	Alum. Epoxy/Urethane	SP-2	May 87
45W	Alum. Epoxy/Urethane	SP-6	Oct. 87
24W	Alum. Ureth./Urethane	SP-6	Sept. 87
	Epoxy Systems (6)		
9W	Epoxy Mastic/Epoxy Mast.	SP-6	June 87
17W	Epoxy Mastic/Urethane	SP-6	July 87
18W	Epoxy/Urethane	SP-6	July 87

32W	Epoxy/Urethane	SP-6	Oct. 87
27W	One Coat Epoxy	SP-6	Sept. 87
29W	One Coat Epoxy	SP-6	Oct. 87
	Inorganic Zinc Systems (8)		
34W	H_2O Inorg. Prime/Silicone	SP-6	Oct. 87
30W	H_2O Inorg. /Acryl	SP-10	Oct. 87
42W	Inorg. Zinc/Vinyl	SP-10	Oct. 87
46W	Inorg. Zinc/Vinyl	SP-10	Oct. 87
14W	Inorg. Zinc/Epoxy/Ur.	SP-6	June 87
35W	Inorg. Zinc/Epoxy/Uret.	SP-10	Oct. 87
39W	Inorg. Zinc/Urethane	SP-6	Oct. 87
12W	Inorg. Zinc/Vinyl	SP-10	June 87

Performance evaluation of the coatings were done after 1, 8 and 20 years. The 1-year performance evaluation 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 (1), 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 (1). 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 3. 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 3 - 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 1 and 2. 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) (change legend in figure according to text) 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.

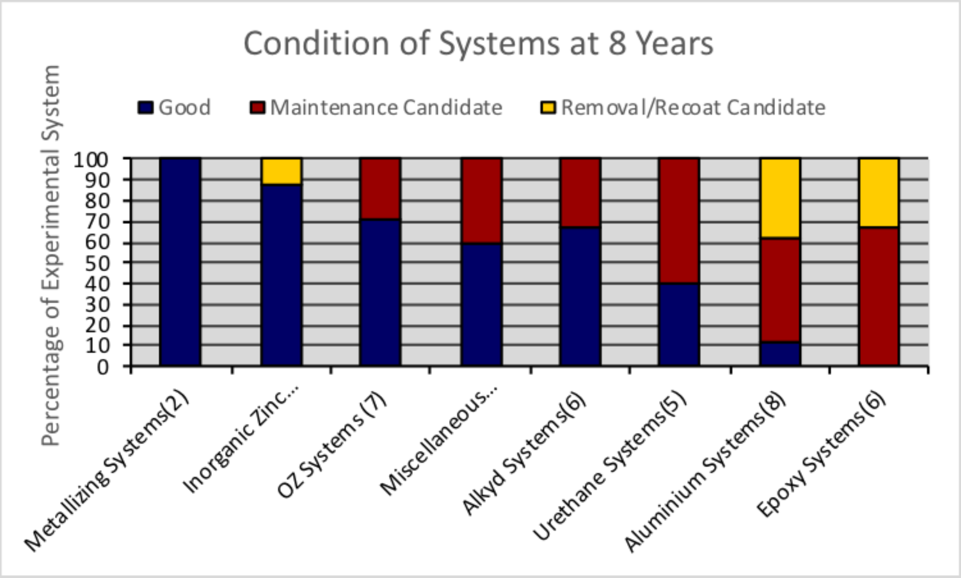


Figure 14. Condition of Systems at 8 Years from Mathis Bridge Study

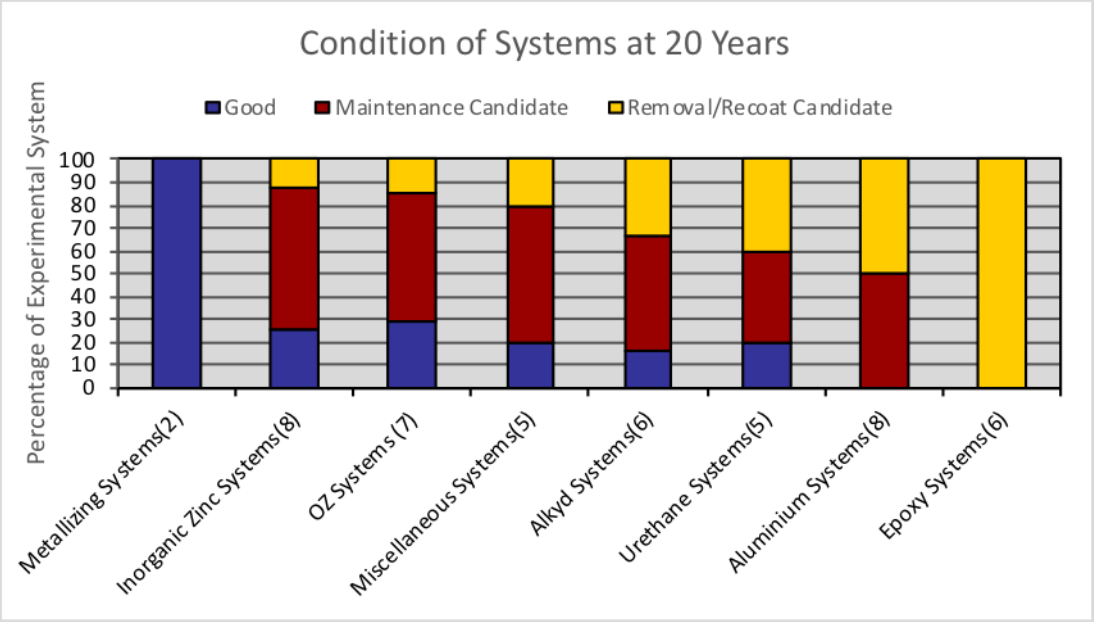


Figure 15. Condition of Systems at 20 Years from Mathis Bridge Study

A careful review of the results presented in Table 3 and Figures 14 and 15 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 15. After 8 years of exposure none of the systems had a rating higher than 7 and after 20 years of 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 as also reported in NJDOT Mathis Bridge Study (33).
- 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 Between Performance of Coatings on Bridges and General Applications

There is a strong correlation between the performance of coating applied to bridges and other industrial structures. Comparing the performance of various coatings presented in Table 1 and the long-term performance of coatings on bridges in Mathis Bridge Study (33), the following observations can be made that are useful to develop a model for correlating the accelerated test results to field performance. Note that the results presented in Table 1 are based on extensive field data over decades whereas the bridge data for long term prediction is limited.

- In both cases metalizing systems provide the best performance followed by coatings with zinc-based primers.

- Severe industrial exposure effects are similar to the exposure at critical locations of the bridges such as locations under expansion joints where the salt-contaminated liquids flow over the coatings. Suspended debris could create more harsh conditions for bridge coatings. Note that these locations consist of a major part for Over-coatings, which is the primary focus of this investigation.
- Effects of surface preparation is also similar for both types of exposures.
- Difference between inorganic and organic zinc-primers is more distinct in industrial coating applications. However, inorganic zinc-primer coatings performed better than organic zinc-primer coatings in both cases.
- Presence of nuts and bolts present a special challenge in bridge applications because the application of uniform thickness coating is a challenge and the beams with more bolts and nuts are typically located under the expansion joints and hence exposed to harsher environments.
- A careful review of all the data indicates that the three levels of exposure namely: mild, moderate and severe have correlations for bridge surfaces that are flat and wide such as large webs and flanges, edges of flanges and locations under joints, respectively.

In summary, it can be stated that data available for industrial structures can be used to predict the useful lifespan of coatings applied on bridges with acceptable accuracy. A number of bridges in New Jersey were inspected for possible correlation with the aforementioned data. These bridges are listed in Table 4. However accurate detailed information could not be obtained for proper correlation. The corrosion process does match qualitatively with the data.

Table 4 - List of NJDOT Maintained Bridges Inspected for Documenting Corrosion Status

Location	Mile Posts	Comments
Route 287 South and 440 North		
287	5.8	Corroded
	3.8	Corroded construction zone
	1.0	Corroded, graffiti, 3 bridges
	1.2	Spot corrosion
440	1.0	Corroded
	1.4	Good Condition
	1.6	Corroded, construction zone
	2.6	Good condition
	2.7	Good condition
	2.8	Good condition
	3.0	Construction zone, Painted on 2008?
	3.2	Good condition
	3.4	Corroded
	3.6	Good condition
440 North Bound	3.2	Corroded
	3.0	Corroded
	1.4	Good condition
	1.0	Corroded
	0.4	Good condition
	0.3	Good condition
287 North Bound	1.8	Corroded
	3.8	Corroded
	5.8	Corroded
	6.4	Corroded
	7.7	Corroded
	13.4	Corroded
	13.8	Good condition
	14.2	Corroded at bolt connections
Route 1 North	Milltown Road	Corroded
	Ryders Lane	Corroded
Route 18 North	College Avenue	Corroded
	Under Riverside Dorms	Corroded
	John Lynch Bridge	Corroded
	Landing Lane Bridge	Corroded
	Busch Campus Exit	Corroded

METHODOLOGY

The creep growth measured using adhesion strength of coating systems subjected to accelerated corrosion were used to predict the expected service life of coatings for transportation structures. The details of the accelerated test method can be found in Balaguru (4) Corrosion growth in accelerated test conditions, obtained over a period of 100 days, is correlated to the expected service life under field conditions. The following are the key concepts and assumption used for developing the correlation model.

- The prime coat sacrifices itself to protect the steel surface. The top one or two coats protect the prime coat by preventing the chemicals and moisture reaching the prime coat. Therefore all 2 or 3 coats plays a role on extending service life of coatings. However, the prime coat plays a major role because many variables such as projectile can damage the top-coats.
- The primary mechanism for the deterioration of prime coat is the development of corrosion cells.
- The factors causing deterioration of topcoats are UV radiation and chemical exposure damage.
- Coefficient of thermal expansion of organic polymer-based coatings are substantially different from the coefficient of thermal expansion of steel. If organic polymers are used in the base coat, this aspect plays a major role in the deterioration of this coat. The authors believe the deep freeze-cycle introduced in the current accelerated test method, which resulted in the enhancement of acceleration of corrosion supports this observation.
- Organic polymers do become brittle over time and results in rapid degradation of top layers. Some epoxies could become very brittle in less than 5 years. The variations in service life of coatings with similar primers can be attributed to this behavior.
- Rolled steel sections were used for the accelerated tests.
- Progress of corrosion does not affect the adhesion strength of coatings at non-corroded areas. This was confirmed by FHWA (17).
- Effect of surface preparation is incorporated in the model using a reduction coefficient if surface preparations is not white metal or “Blast”.
- The top protective coats will prevent the moisture to reach the steel surface for a certain duration. This will depend on how well the coatings were applied and durability of these coats against UV radiation and aggressive chemicals such as salts used to manage snow accumulation during the winter weather.
- Based on the data presented in Table 1, it is assumed that the protection of top-coats can last for an average of 4 years if the requirements of color and thickness changes presented in the procedure section are satisfied. If the requirements are not met, this period is assumed to be 1 year.

Summary of Accelerated Strength Testing Results

The following is the summary of test results taken from Balaguru (4). Essentially, a circular patch of coating 20 mm in diameter was subjected to accelerated test cycles consisting of wet-dry chemical exposure, UV radiation and deep freeze-thaw. Corrosion progressed from the perimeter of the circle towards the center. The adhesion strength of the patch was measured at various stages of corrosion and mathematically converted into reduction of radius of the patch and corrosion creep growth. Procedure for converting the adhesion strength to estimate average creep growth is presented in section "*Interpretation in Pull-off Tests"* in Balaguru (4). Reduction in radius and average corrosion creep growth with respect to the number of cycles of exposure are presented in Figures 16 to 21 for 6 coating systems. The 6 coating systems were chosen based on the performance of Mathis Bridge study (31), representing weak and strong coating systems. The last 2 systems that provided strong performance, Figures 20 and 21, had zinc-based primer, whereas the other four systems did not have zinc-based primers. It can be seen that the progression of corrosion is rapid for non-zinc primers as compared to zinc-based primers, confirming the trend established by a number of researchers. Data presented in Table 1 also shows that even a single coat system using zinc provides performance that is comparable to 3 coat systems.

The following trends can be observed in terms of progression of corrosion growth from a location where the top-coats are damaged. Note that the information presented in the graphs, Figures 16 to 21, is based on the progress of corrosion from an exposed metal subjected to accelerated corrosion. More details of the sample and the accelerated corroding procedure can be found in Balaguru (4)

- As expected, the corrosion growth is more rapid in the early stages of exposure.
- If the coating system is weak, the rate of corrosion growth also increases in the latter stage.
- Zinc-based primer provides a better performance. Corrosion growth for these systems is less than 4 mm, whereas for the other systems it was more than 6 mm.
- Inorganic zinc provides slightly better performance as compared to organic zinc.
- The growth rate measured using adhesion strength results were also confirmed by physical measurements of corroded part of the patch.
- The best performing systems were shown to have corrosion creep growth of 2 mm or less in standard ASTM test methods. The authors believe that the exposure conditions used for the investigation reported in Balaguru (4) resulted in enhanced corrosion rate due the circular geometry of exposed surface and addition of deep-freeze thaw cycle. Note that in standard methods, corrosion is measured from a straight cut.

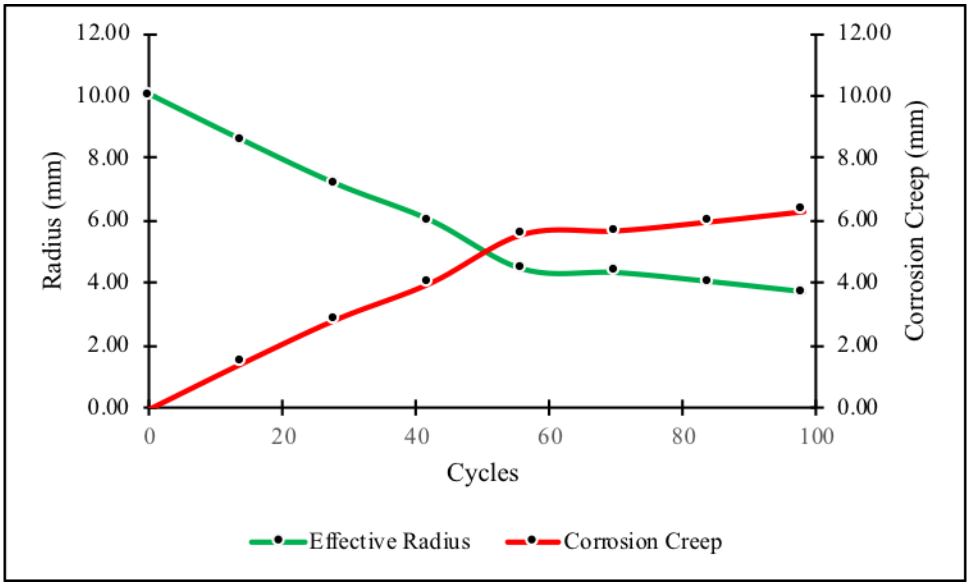


Figure 16. Effective Radius and Corrosion Creep Growth versus Number of Cycles: Coating 1

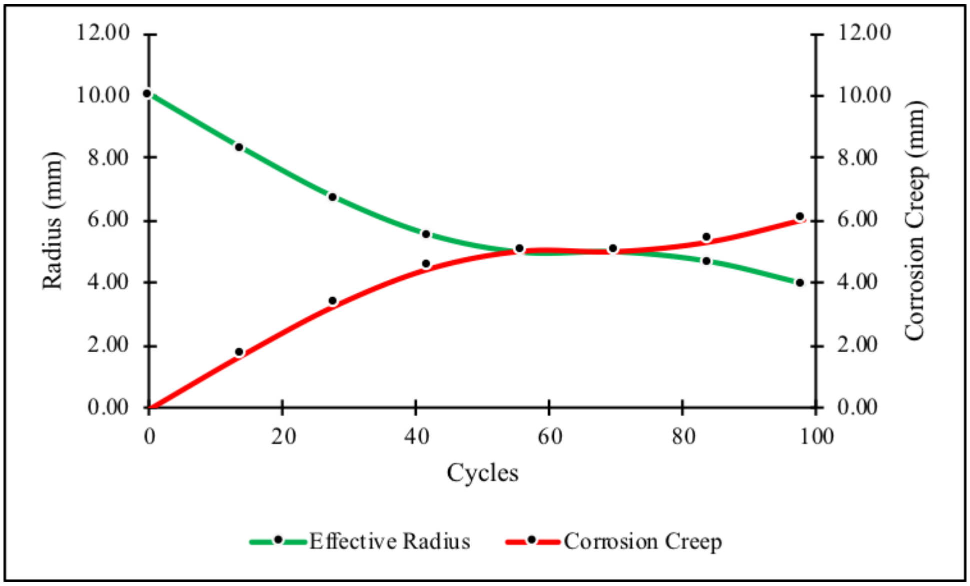


Figure 17. Effective Radius and Corrosion Creep Growth versus Number of Cycles: Coating 2

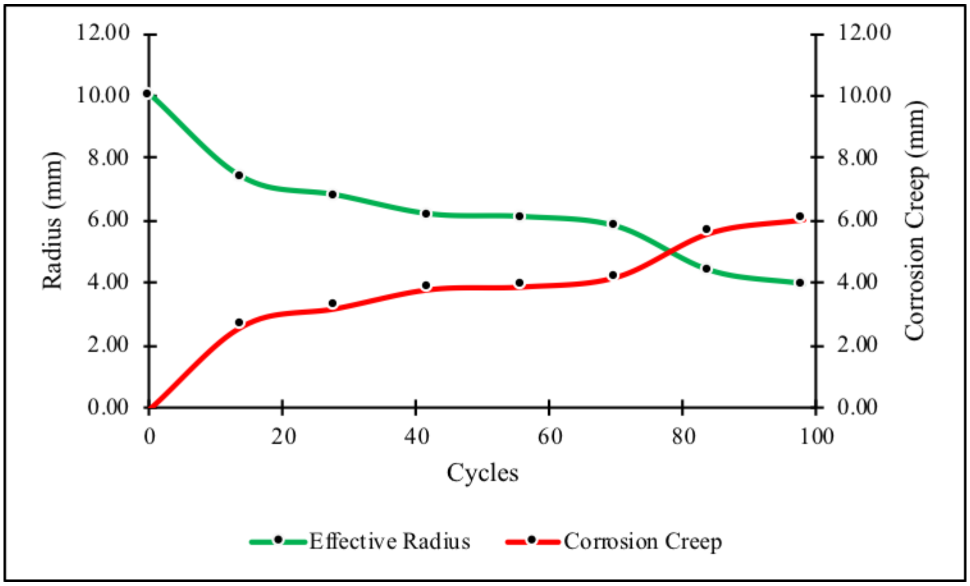


Figure 18. Effective Radius and Corrosion Creep Growth versus Number of Cycles: Coating 3

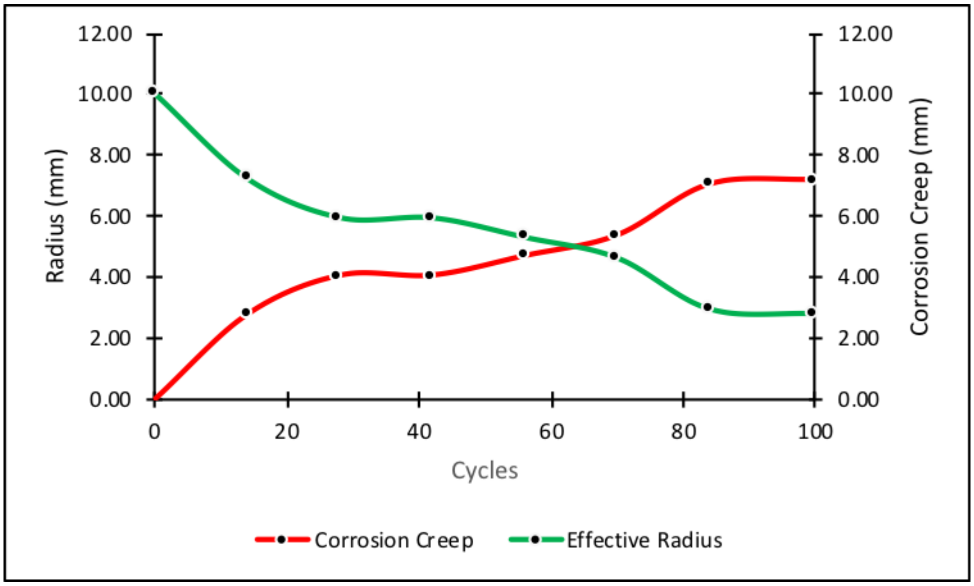


Figure 19. Effective Radius and Corrosion Creep Growth versus Number of Cycles: Coating 4

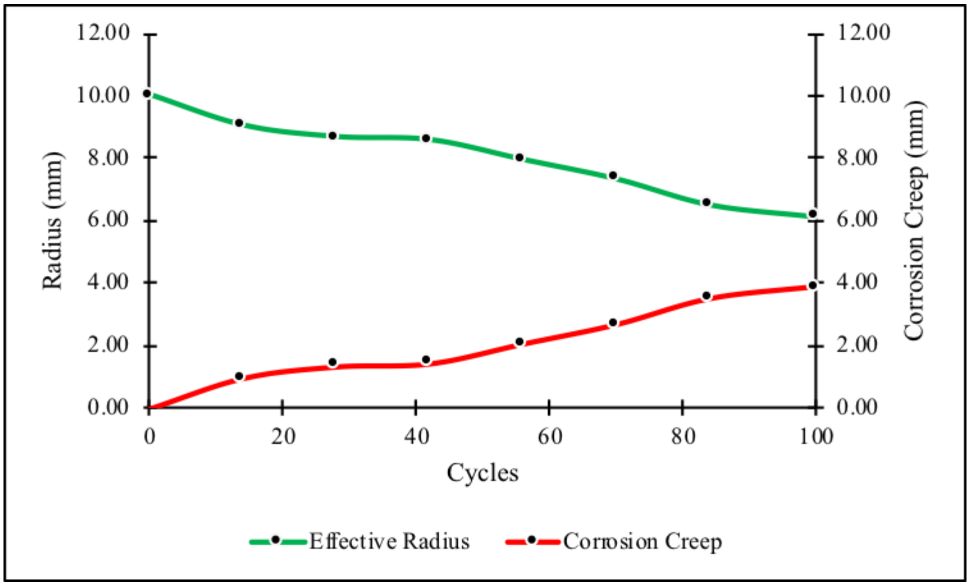


Figure 20. Effective Radius and Corrosion Creep Growth versus Number of Cycles: Coating 5

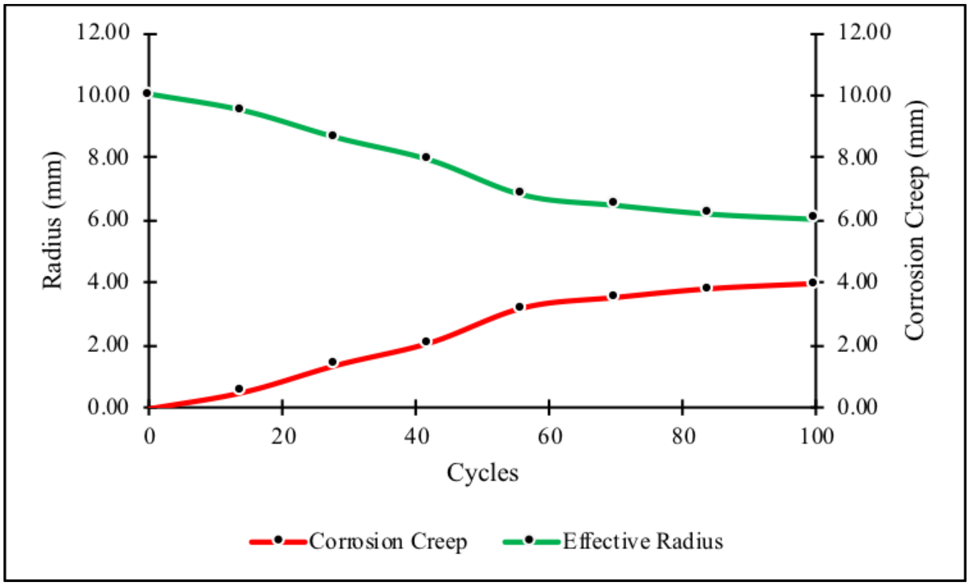


Figure 21. Effective Radius and Corrosion Creep Growth versus Number of Cycles: Coating 6

The following steps were used to develop the model to predict the service life of coatings using the accelerated testing results. The details of the accelerated test can be found in Balaguru (4)

- Develop a regression equation for the corrosion creep growth occurred in accelerated test.

- Develop a correlation between weighted average of constants of regression equations and the field performance data.
- Use the correlation equation for predicting the service life of new coatings for which field data is lacking.

Regression Equations for the Creep Growth of Accelerated Tests

Creep growths of 6 coating systems tested for 100 accelerated test cycles are presented in Table 5. Creep growths range from less than 4 mm to more than 7 mm over the 100 cycles of exposure. Various forms of equations including algebraic, trigonometric, exponential and logarithmic were evaluated for regression models. The algebraic forms were chosen because they provided excellent correlation and they are simple to visualize. Linear, quadratic, cubic and fourth order regression equations were developed for all the 6 coatings. Even though quadratic and cubic equations provided acceptable correlation, fourth order equations were chosen to represent the variations because the computer use is very common and developing these equations do not require much effort. The correlation coefficients for all 6 coatings exceeded 0.999. The details of fitted curves are presented in Table 6. The accuracy of the equations can be visually seen in Figures 22 and 23, representing 3rd and 5th coating systems, respectively. For each regression model of each coating, the constants and the coefficient of correlations are presented.

The typical form for the algebraic equation is:

$$y = c_1x + c_2x^2 + c_3x^3 + c_4 x^4$$

where y is the creep growth in mm
and x is the number of cycles

Table 5 - Corrosion Growth for Six Coating Systems under Accelerated Test Conditions and Fourth- order Algebraic Equations

	Coating System											
NJDOT ID	EU-04		EU-13		EU-16		EU-04		OEU-29		IEU-25	
Primer	Epoxy Mastic Aluminum II		Epoxy Mastic Aluminum II		Bar Rust 235		Carbomastic 615		Zinc Clad III HS		Carbozinc 11 HS	
Over Coat/ Intermediate layer	Carbomastic 615		Carbothane 133 LV (white)		Devthane 359		Carbothane 133 LV (white)		Macropoxy 646		Carboguard 893	
Final Coat									Acrolon 218 HS		Carbothane 133 LV	
Number of Cycles	Lab	Model	Lab	Model	Lab	Model	Lab	Model	Lab	Model	Lab	Model
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	1.47	1.34	1.74	1.74	2.66	2.60	2.77	2.96	0.96	0.97	0.52	0.49
28	2.85	2.89	3.32	3.35	3.22	3.42	4.04	3.84	1.33	1.28	1.37	1.33
42	4.00	4.26	4.50	4.47	3.82	3.60	4.05	4.10	1.43	1.52	2.07	2.24
56	5.57	5.24	5.06	5.01	3.91	3.86	4.68	4.60	2.06	1.98	3.17	3.01
70	5.68	5.78	5.04	5.15	4.22	4.51	5.37	5.63	2.68	2.71	3.50	3.53
84	5.96	6.02	5.36	5.28	5.63	5.43	7.04	6.83	3.50	3.50	3.77	3.81
98	6.28	6.26	6.06	6.07	6.06	6.13	7.19	7.26	3.89	3.89	3.94	3.93

Table 6 - Values of Constants for the Algebraic Equations and Correlation Coefficients for the Six Coating Systems

Coating 1: EU-04					
Primer			Epoxy Mastic Aluminum II		
Overcoat/Intermediate Layer			Carbomastic 615		
EU04	**R-squared**	**c1**	**c2**	**c3**	**c4**
Linear	0.9712	0.076311			
Quadratic	0.9978	0.1258	-0.00063		
Cubic	0.9981	0.1124	-0.0002	-3.1E-06	0
4th Order	0.9987	0.07607	0.001923	-3.9E-05	1.88E-07

Coating 2: EU-13					
Primer			Epoxy Mastic Aluminum II		
Overcoat/Intermediate Layer			Carbothane 133 LV (white)		
EU13	**R-squared**	**c1**	**c2**	**c3**	**c4**
Linear	0.954	0.072398			
Quadratic	0.9955	0.1315856	-0.00075		
Cubic	0.9984	0.1695	-0.00198	8.82E-06	
4th Order	0.9999	0.1166	0.001118	-4.4E-05	2.74E-07

Coating 3: EU-16					
Primer			Bar Rust 235		
Overcoat/Intermediate Layer			Devthane 359		
EU16	**R-squared**	**c1**	**c2**	**c3**	**c4**
Linear	0.9532	0.068112			
Quadratic	0.9768	0.1101291	-0.00054		
Cubic	0.994	0.197	-0.00333	2.02E-05	
4th Order	0.9984	0.2833	-0.00838	0.000106	-4.5E-07

Coating 4: EU-04					
Primer			Carbomastic 615		
Overcoat/Intermediate Layer			Carbothane 133 LV (white)		
EU04 Carbo	**R-squared**	**c1**	**c2**	**c3**	**c4**
Linear	0.964	0.082214	-	-	-
Quadratic	0.9828	0.1272059	-0.00057	-	-
Cubic	0.9925	0.2054	-0.00309	1.82E-05	-
4th Order	0.9989	0.3316	-0.01047	0.000144	-6.5E-07

Coating 5: OEU-29					
Primer			Zinc Clad III HS		
Overcoat/Intermediate Layer			Macropoxy 646		
Final Coat			Acrolon 218 HS		
OEU-29	**R-squared**	**c1**	**c2**	**c3**	**c4**
Linear	0.9924	0.039684			
Quadratic	0.9924	0.03947	2.72E-06		
Cubic	0.9943	0.05612	-0.00053	3.87E-06	
4th Order	0.9996	0.1103	-0.0037	5.79E-05	-2.8E-07

Coating 6: IEU-25					
Primer			Carbozinc 11 HS		
Overcoat/Intermediate Layer			Carboguard 893		
Final Coat			Carbothane 133 LV		
IEU-25	**R-squared**	**c1**	**c2**	**c3**	**c4**
Linear	0.9863	0.045842			
Quadratic	0.9942	0.06199	-0.00021		
Cubic	0.9984	0.03365	0.000706	-6.6E-06	
4th Order	0.999	0.01334	0.001893	-2.7E-05	1.05E-07

Table 7 - Comparison of the Four Regression Equations: Corrosion Growth at 100 cycles from Strong to Weak Coating

Linear	4.6	4.0	6.8	7.2	7.6	8.2
Quadratic	4.1	4.0	5.6	5.7	6.3	7.0
Cubic	3.9	4.2	6.4	6.0	6.1	7.8
Fourth Order	3.7	3.9	5.5	6.3	6.6	7.5
Experiential	3.9	3.9	6.1	6.1	6.3	7.2

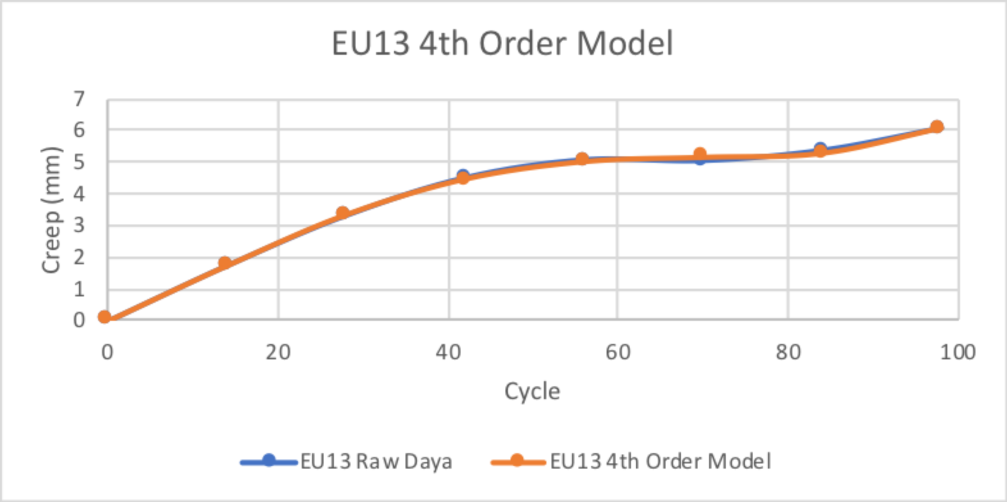


Figure 22. Creep Comparison for Lab and Fourth Order Model for Coating 3.

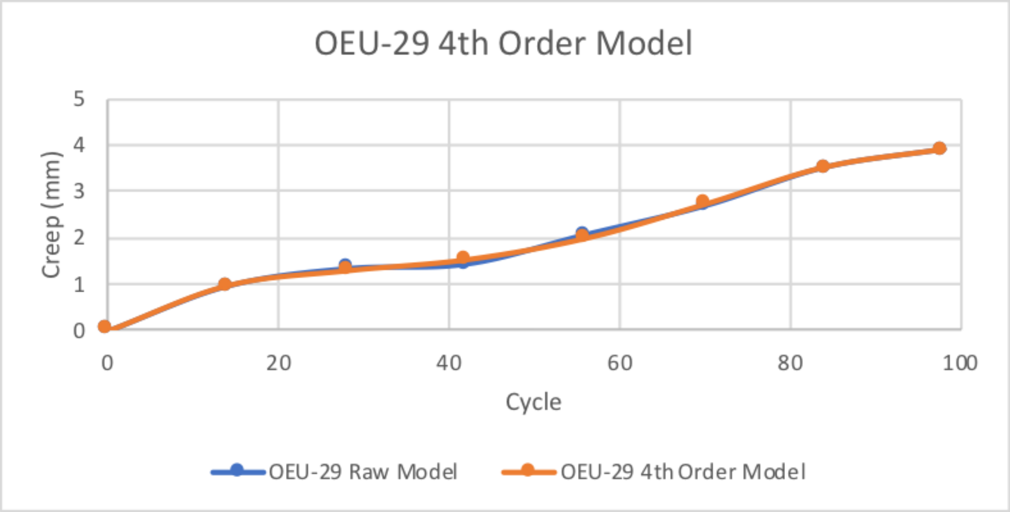


Figure 23. Creep Comparison for Lab and Fourth Order Model for Coating 5.

A careful review of results presented in Tables 6 and 7 lead to the following observations.

- Cubic and fourth order models provide excellent accuracy for all 6 systems.
- Variations of accuracy among the different coatings, even in linear form, are not significant.
- An excellent trend exists between the constants and corrosion resistance provided by the coatings.
- If performance of coating is correlated to constants of the equation, the results are consistent at all four levels of algebraic equations. For example, the order of performance, best to worst, remains the same from linear to fourth order equations. In addition, this performance order coincides with the experimentally measured corrosion growth at 100 cycles of exposure.

Fourth order algebraic equations were chosen to represent the corrosion growth. These equations were used to estimate the service life of coatings under field conditions. Equations for the six coating systems are as follows.

$$Coating-1: y = 0.07607x + 0.001923x^2 - (3.9E-05)x^3 + (1.88E-07)x^4 \quad (1)$$

$$Coating-2: y = 0.1166x + 0.001118x^2 - (4.4\,E-05)x^3 + (2.74E-07)x^4 \quad (2)$$

$$Coating-3: y = 0.2833x - 0.00838x^2 + 0.000106x^3 - (4.5E-07)x^4 \quad (3)$$

$$Coating-4: y = 0.3316x - 0.01047x^2 + 0.000144x^3 - (6.5E-07)x^4 \quad (4)$$

$$Coating-5: y = 0.1103x - 0.0037x^2 + (5.79E-05)x^3 - (2.8E-07)x^4 \quad (5)$$

$$Coating-6: y = 0.01334x + 0.001893x^2 - (2.7E-05)x^3 + (1.05E-07)x^4 \quad (6)$$

The constants of the equations were correlated to service life of coatings under field conditions. The correlations were developed only for the severe field exposure conditions. Note that over-coating applications are needed only in locations where the exposure conditions are severe. Service life range was chosen between 2 and 20 years based on data available for bridges and for general applications. The model development consisted of the following steps. Justifications are provided where needed.

- Compute the weighted average of the constants of the equation. Weighted average is computed as: $100\ c_1 + 100^2\ c_2 + 100^3\ c_3 + 100^4\ c_4$. This weighted average is equivalent to the corrosion growth in mm at 100 cycles of accelerated test conditions exposure. The average values for the worst and best performing coatings were: 3.7 and 7.2 mm respectively.

- Referring to Table 1, the service life of worst and best coatings under severe exposure conditions are: 2 and 17 years respectively. Metalizing coatings were not included in the model.
- The service life presented in Table 1 is based on the performance of entire coating systems including prime and top-coats, whereas the corrosion growth rate in the laboratory was measured from a simulated damage location. Therefore, additional years of service have to be added for any prediction obtained using the laboratory corrosion growth results. These additional years of service is correlated to change in color and thickness reduction of the top-coats.
- Assuming the coating will last from 1 to 14 years after the damage to top-coats occur and the corresponding corrosion growth under test conditions are 3 and 8 mm, expected service life can be estimated using the equation:

- Estimated Service Life in years, Y = 28 – 3 X (corrosion growth in mm at 100 cycles of exposure) + additional service life provided by the top-coats. Since the experimental data available is not extensive a linear regression equation was chosen.

- Additional life provided by the top-coats can be estimated by the color change parameters and reduction in thickness at 50 and 100 cycles. It is assumed that for severe exposure conditions and presence of bolted or welded connections, this additional life is assumed to be between 1 and 3 years.

PROCEDURE

- Conduct the accelerated corrosion test using the procedure outlined in Balaguru (4).
- Obtain an equation relating Corrosion growth and number of exposure cycles using a curve-fitting method.
- Estimate the service life using Equation presented in the previous section.
- Apply the correction factor for surface preparation using Table 1. For surface preparation done using hand tools, this correction factor can be assumed to be zero.
- Add 1 to 3 years for structures with welded or bolted connections and 1 to 5 years for surfaces with less connections.

CONCLUSIONS

- To the best of author's knowledge, currently field performance of the coating systems cannot be predicted using accelerated test results. The procedure presented in this report is the first attempt to predict the field life of coating using accelerated test results.

- A recently developed test protocol made it possible to make the prediction because the results of the new protocol provide consistent and clearly measurable corrosion growth at various stages of accelerated corrosion.
- More research is needed for better quantification of the degradation of the top protective coat.

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