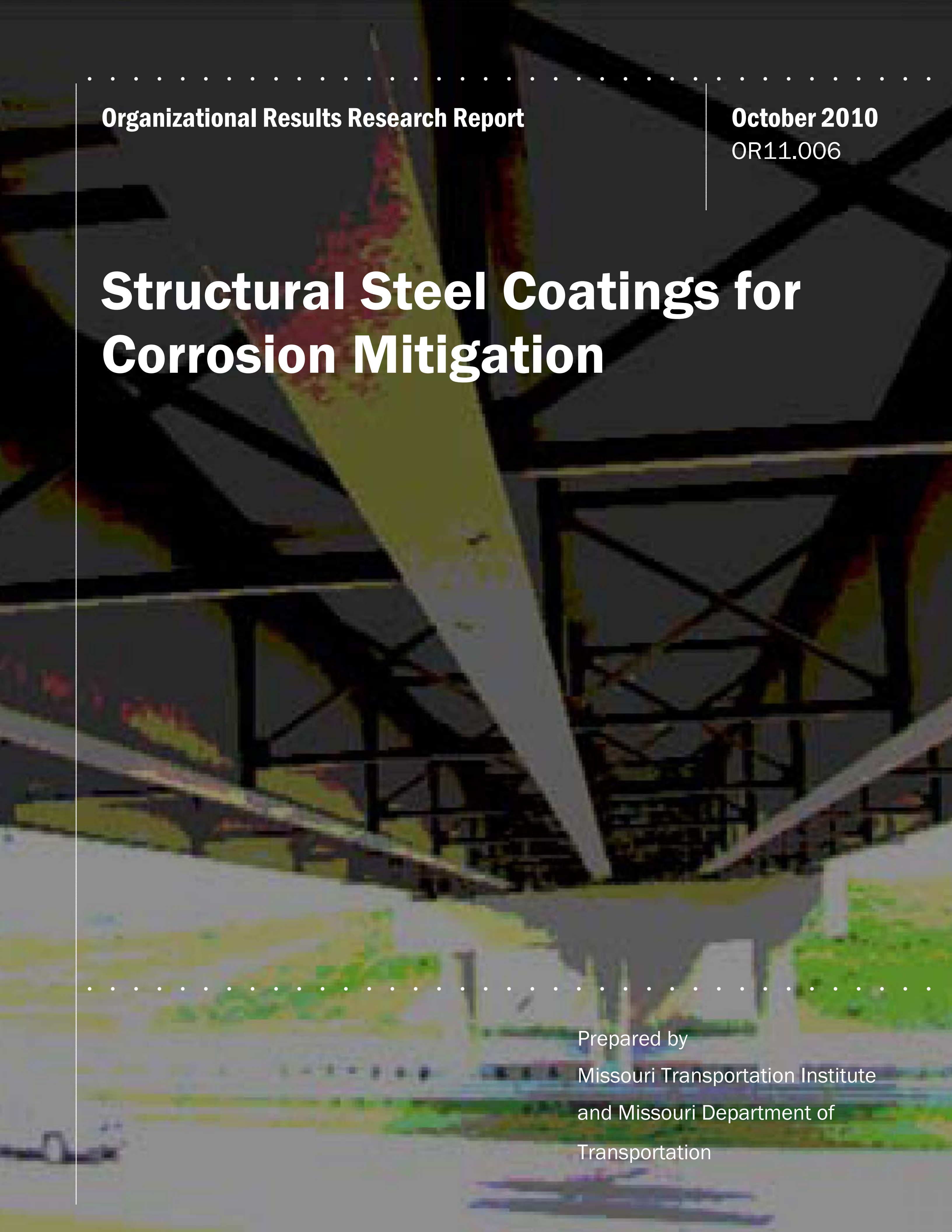

Organizational Results Research Report

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Structural Steel Coatings for Corrosion Mitigation

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Missouri Transportation Institute
and Missouri Department of
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FINAL Report

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Structural Steel Coatings for Corrosion Mitigation

Prepared for
Missouri Department of Transportation
Organizational Results

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16. Abstract

Task 1 of this project was to survey the performance of coating systems for steel bridges in Missouri and to evaluate coating and recoating practices. Task 1 was led under the direction of Dr. Glenn Washer from the University of Missouri located in Columbia, MO. A specific literature review focused on current state-of-the-practice for overcoatings, bridge coating assessment and rating, deterioration rate modeling as well as the risk assessment for overcoating. A new coating evaluation guideline was created to meet the needs of bridge maintenance in Missouri. Finally a field survey was carried out onto the existing bridge coatings across 10 Missouri Department of Transportation (MoDOT) districts and 26 counties. It was found that system S and G perform very well in many of the situations observed. The survey indicated that in many cases system S overcoatings are providing service life extension for the coating system, with some early failures resulting from severe exposure to deck drainage and corrosion. Deck condition, drainage, and joint conditions were found to be the dominate factor in deterioration of the coating system, regardless of the age of the coating.

Task 2 of this project investigated the performance of new types of coating technologies on bridge corrosion mitigation and was led under the direction of Dr. John Myers from the Missouri University of Science and Technology located in Rolla, MO. Twelve coating systems including MoDOT system G were evaluated through several laboratory tests to study and predict the field performance and durability of new coating technologies. The new coating systems investigated in this study involved polyurea, polyaspartic polyurea, polysiloxane polymers and fluoropolymer. To date, these coating system technologies have not been used as a steel structural coatings system in the State of Missouri by MoDOT. The laboratory tests consist of freeze-thaw stability, salt fog resistance, QUV weathering and electrochemical tests. The comparison study was carried out to benchmark and understand the pros and cons of these new coating systems. In addition, two coating systems served as overcoating studies for lead-based paint systems representative of older existing bridges in the state of Missouri. These overcoating systems were evaluated using an accelerated lab test method and electrochemical test. The performance of the existing MoDOT calcium sulfonate (CSA) overcoating system (system S) was also studied within the test matrix for comparative purposes. The test results show that moisture cured urethane micaceous iron oxide zinc/polyurea polyaspartic is a promising coating system for recoating of new steel bridges and that aliphatic polyaspartic polyurea can also be applied on existing coatings after the surface is properly prepared.

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EXECUTIVE SUMMARY

This research project entitled, *Structural Steel Coatings for Corrosion Mitigation*, is separated into two major tasks. Task 1, entitled *Evaluation of Coating System Performance in Missouri*, investigates the effectiveness and performance of the existing structural coating systems that have been used in Missouri. This study reports on the state of the practice for coating and overcoating of steel and evaluates the performance of existing coating in Missouri. Task 2, entitled *Evaluation of Advanced Coating Systems*, identifies and investigates new technologies that hold promise for improved system(s) for coating structural steel structures in the field. The task provides recommendations and investigates a broad range of new coating types. The study results in recommendations that report improved coating performance for structural steel with a low risk of failure based on a series of laboratory tests.

The following conclusions and recommendations were obtained by accomplishing the above two tasks:

- An improved visual inspection procedure and associated visual guides provided through task 1 will improve the reliability of condition assessments for existing coatings systems. Implementation of the recommended procedure will improve the quality of database information available to decision makers.
- The survey of the performance of coating systems used in Missouri showed that maintenance overcoating system S was effective in extending the service life of coating in many cases. The estimate of 10 to 15 years of service life for a well-applied system S coating was supported by observations in the field. However, when overcoating at locations where corrosion was very significant and drainage patterns (i.e. leaking joints) are unchanged, early system S failures were observed. This is due to the combination of existing rusting not being fully removed by the surface preparation, chlorides remaining on the surface, and the continued exposure to wet-dry cycles.
- For coatings overall, the drainage of water from the deck onto the superstructure was the primary factor leading to service failure of the coating. Deterioration of the bridge deck to a poor condition is directly related to the failure of the coating system, regardless of the coating system. Coating systems with 35 to 40 years of service life were still performing well on bridges with effective drainage that kept the superstructure dry.
- The contemporary coating system G was performing well in all situations observed. This modern coating is accompanied by improved designs that avoided water from the deck draining onto the superstructure.
- Every coating system has pros and cons. There is not one panacea for all the conditions. It is of importance to make a case-by-case study when making the decision on which type of paint should be used on a specific bridge.
- Inorganic (IOZ) vs. organic zinc (OZ) primers: IOZ is good at hindering corrosion. However, OZ primer has a higher adhesive strength.
- Coating system-micaceous iron oxide zinc primer with aliphatic polyurea polyaspartic topcoat resulted in a nearly equal performance: good performance on salt-fog resistance, superior resistance to UV and good freeze-thaw stability.
- Aromatic polyurea can be considered to be used at locations where aesthetic appearances (color) are not a first or top priority consideration; for example, the inside surface of steel box girders.

PART I REPORT

TASK 1:

EVALUATION OF COATING SYSTEM PERFORMANCE IN MISSOURI

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1. INTRODUCTION

Significant maintenance costs are expended nationwide each year for coating structural steel bridge elements in an effort to protect them from corrosion and deterioration [1]. Coating of structural steel presents a significant, costly maintenance challenge that is critical to mitigating the detrimental effects of corrosion to extend the service life of bridges and reduce operational costs. The field performance of coatings can be inconsistent, being affected by the quality and method of surface preparation, the environment surrounding the bridge, presence of chlorides and corrosion products on the surface of the steel, and the type of coating utilized. To address this problem, an effort was initiated to survey the performance of coating systems in the field in Missouri, to evaluate how recoating and overcoating practices in Missouri were performing, and to identify needs for future coatings options. This report documents the survey of bridge coatings conditions in Missouri.

Previous work conducted by MoDOT personnel included forming a task force to address coatings issues in Missouri. The Bridge Coatings Task Force included coatings contractors, fabricators, bridge engineers, a chemist, consultants and field personnel. Activities undertaken by this task force included surveying nearby states regarding coatings practices and evaluation of the existing coating systems that could be used in Missouri [2].

Currently, MoDOT employs two strategies for coating bridges in the field. An internal coating program utilizes calcium sulfonate alkyd (CSA) to overcoat deteriorated coatings. An important advantage for the application of the CSA is that it is a one-package coating system, that is, it does not require mixture of 2 components, but rather can be procured in a single can for application. This reduces errors and waste that can be associated with other catalyzed systems. This is ideal for maintenance overcoating, where the required quantities of paint can be uncertain. This coating is typically applied with minimal surface preparation that includes hand tool cleaning and solvent cleaning.

A contract maintenance coating program also utilizes CSA for overcoating. Additionally, when conditions warrant, contracts specify the use of System G (blast cleaning and application of a zinc rich primer) for recoating steel. The selection of bridges for contract maintenance coating is based on the visual inspection conducted by Central Office bridge maintenance personnel and District Office bridge or resident engineers. Subjective decisions are made based on the corrosion and section loss present. Additional analysis that contributes to the decision process includes evaluation of thickness and adhesion qualities of the existing coatings to evaluate the risk of overcoating and the presence of lead in the existing coatings. These physical characteristics of existing coating conditions are available on a limited basis generally.

Issues with the recoating program identified by the task force include surface preparation. Due to the cost of disposing of waste from water cleaning, either low pressure washing or high pressure washing, contractors often do not choose this cleaning option to prepare the surface for overcoating. Wording in the MoDOT specification (section 1081.5.3.2) essentially directs the contractor to avoid water washing of surfaces at their discretion. This specification wording increases the risk of failure of coatings being applied over surfaces that have a significant amount of dirt and other organic contamination.

The current MoDOT specifications require that pressure cleaning at pressures below those typically needed to effectively remove chlorides from the surface of the steel. If chlorides are left on the surface of the steel prior to overcoating, corrosion under the new coating can occur. This can result in the debonding of the new coating from the surface, accelerated deterioration and eventual failure of the coating system.

Another key issue identified by the task force is the lack of an established or objective visual assessment tool for the condition evaluation of existing coatings. These evaluations, which are typically done during biennial inspections, are based on the inspector's subjective assessment of the coating condition. Presently, there is limited guidance on how to assess the condition of the coating system and rate the existing system. Based on discussions with MoDOT personnel, it appears that the rating of bridges includes assigning a qualitative rating (Very good, good, fair, etc.) and a quantitative rating of the percentage of corrosion (rusting) on a scale of 0-10 according to the SSPC-Vis 2 standards derived from ASTM D610 scales. SSPC-Vis 2 and ASTM D610 are industrial standards for coating assessment on structural steel. Inconsistencies in the assignment and documentation of the existing coating condition results in limited reliable data from which to assess the current condition of coatings on a system-wide basis. More consistent field evaluations of coatings are needed to assess programmatic needs, identify specific bridges in need of maintenance activities to prolong the life of the existing coating system, and where re-coating will be necessary.

This process can be improved through the development of visual standards that show examples of different ratings to support more consistent and reliable ratings. Additionally, the influence of surface drainage patterns on the typical coating distress and corrosion are such that information about the location on the structure where the conditions exist could greatly improve the value of inspection data. Coating system deterioration is frequently more advanced in the areas of expansion joints, where leakage of the joints results in exposure of the coating to additional wetting cycles and chlorides from deicing chemicals. Dividing a structure into different areas, such as assigning a separate rating to the beam ends and the middle portion of the beams, could potentially make the inspection data results more meaningful for program planning. Based on this need, an evaluation guide has been developed for the field evaluation of coating systems, and is reported herein. This coatings evaluation guide provides a rating scale that is meaningful in terms of potential maintenance activities by identifying condition states that correspond to the condition for which spot painting, over-coating and re-coating are the most viable options for maintaining corrosion protection.

A survey of coating conditions in Missouri was initiated in November 2009 and completed in July 2010. A total of 96 bridges were visited in 26 counties across all 10 of MoDOT's districts. This report discusses background on overcoating practices and current research, discusses the visual guides developed and describes the results of the field survey. The background section of the report provides a review of the current state of the practice and the existing research record regarding coating systems for highway bridges, focusing on overcoating technologies used for maintaining corrosion protection systems on bridges. The following section discusses existing industrial standards for coatings assessment, and previous research on deterioration rate modeling for highway bridge coatings is discussed. A new condition assessment methodology developed through research is presented and discussed. Finally, a summary of the field survey of existing coatings conditions is presented.

2. BACKGROUND

A literature search was completed to evaluate the current coating evaluation technologies and the state of the art for condition assessment for coatings on highway bridges. This included searching available reference standards and specifications to review existing technologies for the evaluation of coatings system. This effort has also included searching contemporary research efforts to develop technologies for the maintenance and management of coating and corrosion protection systems on bridges. A number of documents and references have been reviewed in an attempt to capture the current state of the art for coating systems (focused on overcoating/recoating) and condition assessment.

Generally, information on the condition assessment of coatings focused on highway bridges was not found, with the exception of condition state descriptions proposed for future inclusion in the American Association of State Highway and Transportation Officials (AASHTO) Commonly Recognized Element (CoRE) guide. Visual standards or guides for routine assessment of coating condition during biannual inspections of bridges were not found; industrial standards exists and are described in this report. These industrial standard are generally suitable for evaluation of coating on smaller structural steel components, such as the hardware and components that may be present at an industrial facility. These standards are difficult to apply to a structure on the size of a typical highway bridge, where the range of conditions may span the entire rating scale on different locations across the structure.

As described in the Task Force report, MoDOT faces several challenges in achieving optimum maintenance coating performance given their current limitations on bridge maintenance coating practices. These challenges focus on several specific technical issues, and the subject literature review focused on these issues in an attempt to bring clarity and to consider current strategies. Specifically, these issues are: (1) bridge cleaning and surface preparation practices, (2) performance of bridge maintenance painting systems, particularly Calcium-sulfonate alkyd (CSA) coating systems, and (3) specific bridge coating condition assessment methodologies. In addition, the subject literature review focuses on expectations and risk mitigation as related specifically to bridge overcoating.

2.1 Significant Studies

Overcoating has been studied extensively, and the majority of bridge owner organizations use overcoating as one of the strategies to maintain their inventory [3]. So, there is a significant experience base to draw from on this subject. Studies have been performed over the past 15 years using modern, low heavy metal, low solvent coatings, by Federal, State and Department of Defense (DoD) organizations. The research has produced generally consistent results on many key technical points and there are several published guidelines for overcoating which address points ranging from surface preparation to coating material selection to condition assessment with the intent of risk mitigation. The Society for Protective Coatings (SSPC) has published a “Technology Update” (TU-3) which serves as a consensus guideline for overcoating [4]. FHWA published a “Bridge Coating Technical Note” several years ago which condenses similar technical guidance [5]. Also, the Army Corps of Engineers has published an Overcoating Guideline [6]. All of these documents are reasonably consistent on the major technical points:

- There are several commercially available coating systems which have and can perform well in overcoating applications. These systems are from various different generic coating groups; these generic types include moisture-cured urethane multicoat systems, calcium sulfonate alkyd single coat systems, multicoat epoxy mastic systems, epoxy/polyurethane systems, and waterborne acrylic systems.
- Surface preparation is <u>the key</u> to long term performance of overcoating applications. There are several options for acceptable coating materials which can provide performance; however, as with all of these coatings, the cleanliness of the surface over which a coating is applied is the key factor determining performance.
- Overcoating is most accurately discussed and considered in terms of risk acceptance and mitigation. Overcoating provides an alternative maintenance option that reduces cost and disruption of the highway system; however, with that advantage comes an increased level of risk of early failure of the newly applied system (versus the full blast and repaint approach). That risk can be abated through appropriate existing coating characterization, conscientious surface preparation, and proper coating material selection. The various published guidelines address all of these factors.
- Owners choosing overcoating must manage their expectations for “success.” In all credible studies reviewed, successful overcoating applications fail to approach the performance of a durable coating system applied over properly cleaned (i.e., blast cleaned) steel. For example, in a typical highway environment where the expected life of a new coating applied over blast-cleaned steel may be 15-25 years, the expectations for a successful overcoating application should be in the range of 5-15 years depending on the severity of the specific exposure conditions.
- Choosing an appropriate coating system must be formula specific and not based solely on generic coating type (e.g., epoxy, moisture-cured urethane, calcium sulfonate alkyd, etc.). Coating selection should follow some rational system of qualification and verification of specific products from specific manufacturers. Additionally, periodic sample testing should be used to confirm that paints delivered in bulk, over time, conform to the same chemical makeup as the initial samples submitted for qualification testing as formulations under the same commercial label can and will

change. Many studies have highlighted the wide variation in performance within generic coating types [7].

Overcoating is nothing new. In fact, overcoating is just traditional maintenance painting under modern regulatory and practical constraints. Many of the older steel bridges in the country (particularly toll bridges or "major" bridges) have been overcoated as a regular practice for many years. Prior to some of the more recent major full blast and repaint efforts on older notable steel bridges, it would not be uncommon to find specific areas of bridges that had total paint film thickness (localized) of 100 mils, the result of having been painted over 50-odd times with the same lead-alkyd maintenance paint[8].

The difference in our current interpretation of the term overcoating has arisen in the past 20 years in response to the specificity of the practices and materials that are used for bridge maintenance painting. While traditional maintenance painting (pre-1990) included practices such as lead alkyd-over-lead alkyd applications in "spot painting" and the selective use of open abrasive blasting, and spot blasting, regulations limiting generation of airborne lead dust and limitations on the use of high solvent, heavy-metal pigmented coatings has rendered these practices unviable from a practical and cost perspective. Regulations have changed the once simple maintenance painting approach into the more complex practice known as "overcoating."

2.1.1 The Importance of a Chemically Clean Surface

Visual standards for cleanliness (e.g., SSPC SP-2, 3, 5, 6, & 10) still dominate the industry and can be found in the vast majority of specifications; however, over the past decade it has become widely recognized that non-visible surface contaminants often play a significant role in the ultimate performance of paints systems[9, 10]. Many owners are turning to specific tests for contaminants such as chloride and sulfide on the surface of an apparently (visually) blast cleaned surface. For less-than-ideal surfaces such as those resultant from preparation for overcoating, these surface contamination tests have not gained any popularity primarily due to the fact that surface contamination in these cases is *assumed to exist* and testing would be academic and a waste of resources. Instead, the focus has been on the SP-2/3 visual standards, standards directed toward "characterizing" the physical integrity of the remaining existing coating (to be overcoated) and the never-ending search for the magic can of "surface tolerant" paint. While various paint systems have been shown by research and testing to have surface tolerance in a relative manner versus other paint systems, it remains that the physical and chemical cleanliness of the prepared surface is the primary determining factor (along with subsequent exposure conditions) for paint performance. This is particularly true in cases such as bridge overcoating due to the fact that coating breakdown is most often location specific (e.g., under joints or near drainage, etc.) and the "new" coating is typically applied over a less-than-ideal surface preparation in the very areas where the best surface preparation is required (i.e., the harshest exposure locations on the structure). This often leads to the use of so-called “zone painting” approaches where a mixed job of blasting and power tool cleaning is used on different areas of the same bridge depending on specific needs and exposure severity.

When testing new surface tolerant paint over pre-rusted and contaminated test panels or structures, inevitably the initial failure points will be at the same locations as the previous breakdown. This is due to the invisible contaminants remaining on the “cleaned” surface beneath the new overcoat paint. By washing as many of these contaminants off of the surface prior to new overcoating paint application, a much better success rate is achieved.

2.1.2 Wash Water from Pressurized Water Washing Prior to Mechanical Cleaning

The importance of a clean surface to the performance of coating systems introduces the issue of washing the surface of the steel to prepare for coating application. Requirements to control, collect and clean the wash water from such activities can be a practical limitation that inhibits the application of the most effective washing approaches. The Kentucky Transportation Cabinet published a study in 2003 indicating that conventional filter fabrics and tarps used to “catch and filter” bridge wash water on site are likely ineffective in controlling the lead content of effluent. However, the capture and on-site use of portable sand filters have a significant cleaning advantage and two stage advanced portable filter systems have the likelihood of obtaining drinking water level cleanliness of wash water on site [11].

Other states take similar approaches to the control and treatment of wash water. In general, the state of the practice is represented by the use of screens to knock down wash mist and catch larger paint chips. Impermeable tarps are placed beneath the screens to catch water, and the runoff is controlled by birming into collection areas. From there, contaminated water may be pumped into collection containers or filtered on-site for disposal. Figure 2.1 shows a typical trailer-mounted filtering system that can be used on-site to clean wash water during cleaning operations. There is no doubt that the issue of wash water collection and disposal is one of the more highly variable aspects of industrial painting operations both with regard to practice and level of enforcement. However, effective surface cleaning through water washing is a very common, and technically necessary practice if long term coating performance is to be achieved.

While it is understood that Missouri has had significant restrictions placed on DOT in-house maintenance crews by the Department of Natural Resources, these issues are not unique to Missouri. Every state DOT has had to face similar regulatory challenges regarding the use, collection, testing, and disposal of contaminated wash water. The majority of structure owners have developed policies and pursued some type of water washing as a necessary first step prior to mechanical surface preparation in spite of the push-back from local regulators. Examples include specifications found from New York State, Caltrans, Maryland SHA and others [12,13]. Although enforcement of water regulations has certainly been highly variable across various jurisdictions, at this point, most specifications require a reasonably diligent effort to collect, filter and dispose of contaminated wash waters. Most bridge painting contractors accomplish this with a combination of screens and impermeable tarps used to direct the water to crude, yet controlled collection areas where it may be pumped through filters prior to local disposal.

North Carolina DOT has published a specific guideline for contractors regarding bridge wash water [13]. It contains the following directive:

> "Total containment of the wash water is required. During the bridge washing process, the Contractor must collect; sample, test, monitor, manage, neutralize, filter and dispose of all wash water generated by the bridge washing process."

This statement certainly relates the trend nationwide and it should be assumed that bridge wash water will be required to be contained, tested, and properly disposed of going forward. Given the importance of proper surface preparation and the removal of chlorides and other organic contaminants, pursuit of such specifications and processes for addressing the wash water issue, and associated regulatory relief, may provide the most readily available improvement to current practices under existing constraints.

Figure 2.1 Photo of a Trailer-mounted Multi-stage Filter Rig for Removing Contaminants from Wash Water.

2.2 Performance of Specific Coating Systems in Overcoating

Much of the effort of the industrial protective coatings technical community over the past two decades has focused on the search for the optimum paint product. Most of the testing and research work sponsored by both public and private sources has been focused on comparative testing of the performance of various new and improved paint systems under a myriad of "representative" conditions. While this testing has born significant useful results, it only answers one aspect of the question. Potentially more important to ultimate bridge maintenance paint performance is the performance of the system at the paint/steel and new paint/aged paint interfaces. In a realistic, non-ideal overcoating scenario, it is these interfaces which define the ultimate performance of the system. Performance at these interfaces is difficult to study due to the non-ideal and highly inconsistent nature of the surface both morphologically and chemically, and due to the difficultly in mimicking the aging process for the existing coating; however, there have been several studies which have provided useful insight to this question. Also, there are several other credible studies which have isolated specific major variables in the overcoating question.

Several research studies and many more anecdotal articles are available that characterize the performance of paint systems in bridge overcoating applications. As stated above, there are common threads in the results of many of these studies, particularly with respect to the ultimate importance to performance of the cleanliness of the surface. However, there are also trends in the available data indicating that the coating material selected for overcoating can add or detract from the performance of the system as well. The more popular generic types of industrial coatings used for overcoating applications fall roughly into the following categories: Moisture-cured urethanes, epoxy/polyurethane, low-viscosity penetrating sealers, calcium sulfonate alkyd, and waterborne acrylic. Most interesting among these groups are the moisture-cured urethane and the calcium sulfonate alkyd coatings. These two generic systems represent the two extremes in current philosophy in overcoating material selection. Both are formulated for surface tolerance and both are intended to be somewhat robust relative to application conditions, but they differ in certain key aspects. The moisture-cured urethane systems (available from several manufacturers) represent more of the "mainstream" approach of multiple coats, dry-hard, crosslinked polymer. They also rely on barrier pigmentation to add durability. The calcium sulfonate alkyd materials are intended as single coat applications with very slow dry properties. They have good wetting and high build (for a single coat). They rely on their high pH nature for corrosion inhibition. They do not dry hard and as such, can be susceptible to damage and dirt pickup. The literature shows that both of these types of coatings can perform very well in overcoating applications[1, 10]. The choice between materials should continue to rely upon the specific desire of the bridge owner for damage tolerance, appearance for the specific case and economy of application.

It should be noted that not all materials supplied under a specific generic label will perform the same. It is highly important that the DOT has a systematic approach for selecting qualified products, either through testing or experience. It is also important to perform first article sample testing to ensure received coatings are identical to those tested for performance qualification as paint supply companies have been known to change formulations under similar labels. This practice can have significant effects on the ultimate performance of coating systems.

2.2.1 Calcium sulfonate alkyd coatings [10, 14, 15]

Since Missouri DOT is currently using calcium sulfonate alkyd coatings as their material of choice for in-house maintenance painting work, references citing specific performance results for this type of material were reviewed. Several credible sources were found that have evaluated calcium sulfonate alkyds (from various manufacturers) over the past two decades. These programs all showed calcium sulfonate alkyd to perform very competitively in terms of corrosion protection (rust through resistance and scribe cutback resistance) during controlled tests. Tests reviewed were run in accelerated test cabinets and in various natural exposure test environments. Anecdotal evidence in various sources also indicates good performance relative to other products marketed for overcoating applications. In general, when competitively tested in controlled environments and laboratory conditions, calcium sulfonate alkyd coatings have performed within the top two or three performers in most tests. This indicates that, given its single component nature, calcium sulfonate alkyd is one of the good coatings for an owner to use for this application.

As every coating on the market, calcium sulfonate alkyds are (CSAs) not without their limitations. They tend to dry slowly (depending on specific formulation and environmental conditions) and they tend not to "dry hard" as many of the competitive cross-linked (e.g., epoxy and urethane) systems. This can be an issue with damage and dirt/debris pickup in a highway environment. So, if aesthetics are of primary importance, CSA's may not be the best choice. A recent FHWA report summarized this issue:

> "Overall, CSA performed the best on all three substrates. However, it is a soft material that picks up dirt easily. Given these strengths and weaknesses, the researchers advise bridge owners to use their best judgment in deciding whether to use CSA as an overcoat material."

On the positive side, CSA's do possess many of the properties that can assist a marginal existing paint system in an overcoating scenario. O'Donoghue from Devoe Coatings puts it this way.

> "Penetration, wetting, adhesion, minimal shrinkage stress, and flexibility arguably are the most important characteristics of a good overcoat system. Wetting occurs, in part, by polar attraction and

lowering surface tension. It is advantageous if the primer concomitantly reacts with, or displaces, moisture."

The Northeast States studied overcoating extensively in their NEPOVERCOAT program. Thirteen coatings were originally applied and tested in the NEPOVERCOAT program over varying surface preparation conditions on salvaged steel beams with aged alkyd coatings. Beams were placed at four separate maintenance yards around the Northeast states and sprayed with salt water periodically to make the exposure similar to a highway environment. Performance of the various coatings was difficult to analyze to discriminate a final definitive list of approved coatings. The final list combines the test results with the experience of the DOTs on the committee. This data emphasizes the point that coating materials from various generic types can be successful in overcoating applications, and it is the surface preparation and application conditions, combined with the subsequent exposure that is the correlating factor to performance.

This test program generated a qualified product list (QPL) which presently has 3 products; ironically one epoxy, one high build waterborne acrylic material and one 3-coat moisture cured urethane. Although a variant of CSA was tested and performed relatively well, they did not add CSA to the list due to its tendency to remain soft for a long period after application.

2.2.2 Abstracts of Selected References for Overcoating

This section contains abstracts from several key references for the overcoating of steel bridges. These abstracts were included as references that, when combined, provide a relatively comprehensive overview of overcoating and overcoating issues.

"Special Report: Overcoating Lead Paint," Journal of Protective Coatings and Linings, November, 1993

This special report was issued by the Journal of Protective Coatings and Linings in 1993 as a response to the rapid increase in overcoating of bridges that took place at that time (spurred by the 1993 issue of the OSHA regulation for Lead in Construction). The report serves as an excellent summary and literature review for overcoating practices, materials, and risks at that point in time. The vast majority of the content is still valid today as the issues have not changed. In the ensuing 18 years, research has continued to determine optimum practices and materials performance in overcoating, but none of the subsequent research found contradicts the basic findings of this report.

"Guidelines for Maintenance Painting of Steel Bridges," FHWA-RD-97-092, Draft Report, September 1996.

This report documents research sponsored by FHWA to determine appropriate practices and materials for overcoating. The results point to the importance of surface preparation and original (pre-surface preparation) surface cleanliness to performance of all of the various coatings tested. The research tested 8 separate coatings applied onto two separate locations on four in service bridges around the country. While the findings illustrate that the location of the bridge is certainly important to overcoating performance, and the coating selection can also make a difference, by far the most important factor in ultimate performance is the level of contamination and after-prep cleanliness of the specific steel overcoated. For example, the same set of test coatings applied over deteriorated steel under a leaking joint may fail within 2 years, while those same coatings applied to a less aggressive section of the same bridge may last several years with good performance.

"Evaluation of Selected Maintenance Coatings Over Hand and Power Tool-Cleaned Surfaces," J. Ellor, R. Kogler, Ocean City Research Corp., Journal of Protective Coatings and Linings, December 1990.

This journal article documents research work performed for the US Navy on maintenance painting (overcoating) using marine coatings. These coatings are primarily epoxy based materials, but the test matrix included polyurethane materials and non-lead silicone alkyd topcoats. One of the primary conclusions of the work is highly applicable to the present question of bridge overcoating. The conclusion states," Over the subject test period (20 months of beach exposure), the effect of the cleaning method (SP2 vs. SP3) appears limited. Of more probable importance is the degree of cleanliness achieved." This conclusion points to the fact that all panels, for all coatings tested failed within this short period at areas of the panels that were contaminated with salt and rust deposited prior to cleaning and overcoating. This study, like several others, shows that under conditions of severe (i.e., high moisture and salt) exposure, overcoating applications tend to fail rather quickly in the same areas of the steel that required maintenance painting in the first place. For these areas, success of overcoating depends heavily on the aggressiveness of the surface preparation. That is, a physically and chemically clean surface is required for any of the industrial coatings tested to be successful.

"Selecting overcoats for bridges: FHWA researchers test the corrosion resistance of various paint systems for steel structures," Public Roads, Sept-Oct 2007, S.L. Chong & Y. Yao, FHWA.

This article provides background and results of a FHWA study into the potential use of single coat bridge paint systems in overcoating applications. CALTRANS officials are quoted regarding the necessity of using overcoating due to the large number of bridges which need painting and the limited time and budget to perform this work. CALTRANS is one of the few states besides Missouri which has a significant in-house maintenance crew effort to overcoat bridges.

“We're overcoating the majority of our steel bridges," says Senior Chemical Testing Engineer Andy Rogerson with Caltrans. The department maintains nearly 800 steel bridges statewide. “Most have a red, lead-based primer coat, which for the most part is performing well,” Rogerson says. “When the topcoats start to fail, Caltrans applies waterborne primers and acrylic latex topcoats or, for harsher coastal climates, three-coat, moisture-cured urethane (MCU) overcoat systems.”

“Cost is the main advantage. Overcoat applications cost the agency $6 to $10 per square foot--nearly two-thirds less than the cost of full removal. If rust covers less than 20 percent of a bridge, then we'll keep the lead primer and do an overcoating," Rogerson says.

“Maintenance Issues and Alternate Corrosion Protection Methods for Exposed Bridge Steel,” NCHRP Synthesis #257, T. Neal, 1998.

Virginia DOT performed an overcoating research project in the late 1990’s. Six coating systems (epoxies, polyurethanes and low-VOC alkyds) were applied to bridge structures following steam cleaning and SP-3 power tool-cleaning. All six coatings showed signs of delamination and rust through failure after less than two years. VDOT concluded that the condition of the existing coating on the bridge is the key determining factor for potential success of an overcoating application. If the existing coating is showing signs of delamination, they feel that that bridge is a high risk candidate for overcoating.

3. BRIDGE COATING ASSESSMENT

This section discussed the assessment of existing coating systems, and identifies current references and standards for condition assessment.

General procedures for conducting a detailed assessment of the condition of aged coatings on steel structures can be found in ASTM D 5065- 07, *Standard Guide for Assessing the Condition of Aged Coatings on Steel Surfaces[16]*. This standard describes methods for evaluating the condition of aged coatings on steel surfaces, and evaluating the degree of rusting and other deterioration modes present. The methodology generally includes identifying different types of components a structure consists of, and rating each separately for various forms of coating damage and deterioration, such as peeling, blistering and rust. Areas of the components that have "typical" levels of deterioration are identified for rating as well as localized areas that have greater levels of deterioration due to unique environmental conditions, such as under expansion joints in bridges. The standard also suggests measurement of the thickness and adhesion properties of the coating. A sample form for recording the results of the inspection is included in the standard.

The visual inspection of coatings described in the standard include determining the corrosion level of steel sections based on ASTM visual standards for rust breakthrough (Test method D 610), blistering (Test method D 714), peeling (Test method D 610), chalking (Test method D 4214), and cracking/ checking (Test method D 660). The guide notes that it is important to rate enough components in order to show the general condition of the entire steel structure, and areas that have higher corrosion rates should be noted on the inspection form. The process described provides useful overall guidance on the evaluation of the existing coating systems, although the process is quite detailed relative to contemporary methods utilized for bridges. Such guidance is likely most useful in preparation for specific coatings projects, rather than assessment on the inventory level such as might be done as part of the bridge inspection practice.

3.1 Industrial Visual Guides: ASTM D 610-08 and SSPC-VIS 2

Assessment of the rusting level on a painted steel surface can be accomplished according to visual guides that show the level of rusting according to a subjective visual scale. Visual guides are available from the Society for Protective Coatings (SSPC- VIS2) and ASTM D610, which provide visual standards for assessing the extent of corrosion on the surface of painted steel. Black and white (ASTM) or color (SSPC) photographs represent different levels of rust and associated rating scales to be assigned by an inspector. Estimating the rust level on the steel surface by using different images that represent rust grade in percentage is important to determine coating maintenance approach, and to characterize the extent of deterioration that is present on the steel[17]. Visual standards are a common methodology used to normalize or attempt to standardize the results of visual inspection, which is inherently subjective. The primary goal of the visual standard is to provide a common understanding of different rating levels, to support consistency in the evaluation process, and provide useful inspection results. To rate the extent of corrosion present, inspectors can utilize visual standards provided in ASTM D610-08 and SSPC-Vis 2. In this standardized practice, the degree of rusting is assessed by using a zero to ten scale made of visible exterior rust degree. However, these visual standards provide examples of small surface areas, which can be difficult to utilize on a large structure such as a bridge.

3.1.1 Process of the Assessment Rusting Level

To evaluate the level of rusting, or corrosion, on the surface of the steel, a two-step process of evaluation is used under ASTM/SSPC guidelines. First, the characteristic appearance or distribution of the rust is identified: There are three kinds of rust distribution: spot rusting, general rusting and pinpoint rusting. Spot rusting (S) is used to describe rusting that is localized in nature; General Rusting (G) is used to describe rusting when various size rust spots are randomly distributed across the surface, and Pinpoint rusting (P) is used to describe when rust is distributed across the surface as very small, individual specks of rust [17].

The visual standards provided by SSPC provide 27 color photographs of coated surfaces and black and white figures that show rust percentage for three types of rust distributions (Grade 1 to 10). Evaluating the percentage of the rusted area is accomplished by comparison to the visual sample (photographs) provided. Under the SSPC scheme, the inspector determines the rust grade as a percentage of the rusted area and allocates an appropriate rust grade (0-10) rust type: S for spot, G for general and P for pinpoint. For example, for spot rusting which has a rust grade 6, enter: 6-S [18]. This process may be more appropriate for the evaluation of coatings on components that are not as sizable as a highway bridge, as a typical highway bridge with deteriorating coating may have areas of steel that span all of these ratings and rust distributions. The inspector typically chooses a description that characterizes the overall condition of the coating on the bridge, though this is a subjective process that can vary between inspectors.

A single rust percentage evaluation may have limitations in the sense of analyzing a bridge to determine if spot painting, overcoating or recoating is appropriate for the bridge, or for evaluating the urgency of action in regards to preserving the existing coating system. For example, if spot painting needs could be identified early in the deterioration process, it could extend the life of the coating at a lower cost than letting the coating deteriorate until recoating is needed. Zone painting of the area under the bridge expansion joint, which typically has more significant damage than mid-span due to exposure to deicing chemicals and moisture, may be a viable option for extending the life of the coating system and providing suitable corrosion protection. A methodology is needed to effectively characterize the extent of corrosion that meets the needs for bridge evaluation to assist in planning of future coatings efforts and to develop management strategies for corrosion protection.

3.2 Risk Assessment for Overcoating

SSPC Technology Update No. 3 (SSPC TU-3) provides a methodology for evaluating the risk associated with overcoating. Delamination as a result of internal stresses is the primary risk for overcoating, as the shrinkage of the applied paint transfers stresses to the underlying existing coatings. An additional risk is early rust back or poor coating performance that results in the overcoating not providing the anticipated period of service, due to the severity of the service environment and less than ideal surface cleanliness. The surface preparation used prior to overcoating will affect the performance of the overcoating.

The methodology described in SSPC-TU3 for evaluating the risk of overcoating described many factors that contribute to the likelihood that an overcoating will be unsuccessful, including the existence of mill scale on the steel surface, surface contaminants such as chlorides, and the brittleness of the existing coating. Additionally, thicker coatings tend to be more highly stressed, and the stresses introduced by the application of overcoating can result in delamination of the existing coating. The adhesion of the existing coating, both to the substrate and within the coating itself, is also a critical factor to determine the suitability of overcoating. SSPC TU-3 provides a relatively simple algorithm for evaluating the risk of overcoating considering the film thickness and adhesion of the existing coating to estimate the risk level of overcoating. This methodology has been generally applied for the evaluation of overcoating risk by MoDOT District 6 personnel in the past. This methodology represents the industry standard that has a proven record, though not a perfect record, of success in mitigating the risks of overcoating.

Another key aspect of risk mitigation is the use of a test patch for overcoating evaluation. In general, the available guidance specifies the use of the same surface preparation and same coating intended for the overcoating application in various representative areas of the structure, allowing weathering over at least one winter temperature cycle to ensure coating compatibility through the curing and cold weather cycling the coating will see in service. Such patch testing can help reduce the risk of overcoating. If such a test patch is to be used to assess the overcoating risk, the “representative” sample areas on the bridge should include both currently corroded surfaces, to test the effectiveness of the cleaning and surface preparation, and areas of relatively intact coating. Intact areas of the existing coating system should be tested to evaluate the potential of the overcoating system to cause debonding/adhesion failure of the substrate, cohesion failure within the substrate coating and adhesion failure at the coating/overcoating interface.

3.3 Coatings Maintenance Programs: Current Research

Development of bridge coating maintenance programs is an emerging theme in reviewed research and will be discussed herein. A bridge coating maintenance program serves to maximize the service life of steel bridges through cost-optimized application of maintenance. An effective coating maintenance program first requires a method to identify and track existing bridge conditions. Corrosion growth rates can then be calculated or estimated utilizing trend data, or from prior experience and knowledge of typical coatings characteristics. Given the current condition, corrosion growth rates or estimates of the coating deterioration rate can be used to project the remaining life of the bridge coating. Using known characteristics of differing repair methods, the effect of these methods may be considered with respect to annual life cycle cost in a coatings management program. Recent research has been completed on different approaches to managing coating systems and a few of these are described herein.

3.3.1 Methods for Identifying and Tracking Existing Bridge Conditions

Several approaches utilized for identification and tracking of existing bridge conditions are found in the literature search review; these include spreadsheet methods [19], artificial intelligence methods [20], and deterministic and probabilistic deterioration models [21].

Each method offers advantages and could be selected upon the needs of the maintenance program. Comprehensive, sometimes elaborate coating management programs are available. However, the costs can be high, and the maintenance of the data for the program may require extensive efforts to make the programs provide the desired results. An effective alternative, which can provide a compromise between an elaborate and expensive computer programs and planning coatings activities based on gut instinct or by ad-hoc planning, is to use a simple spreadsheet database that includes a database of the coatings conditions for a given inventory of bridges [19]. By using a spreadsheet it is easy to see bridge coating conditions across the inventory and prioritize the most important conditions to support future planning and prioritization activities. The approach involves use of a spreadsheet program such as Excel to track visual inspection results, measurements, and evaluations of bridge coating deterioration. Suggestions in the literature include that the spreadsheet should include data on the inspection area, item, present coating type, corrosion rate, measurements (thickness and adhesion), preservation method (overcoating, recoating) and cost of painting.

Estimation of the standard corrosion percentage can be done using the SSPC – VIS 2 standards or other suitable standards developed for certain applications. The SSPC standards provide a 10 number scale that may be too detailed for many structural applications such as bridges where coating conditions can span the entire range of the scale at local levels.

Paint thickness is important if overcoating methods will be used and overall coating should be evaluated in order to determine total thickness. The dry film thickness of the existing coating can be measured easily using a magnetic gage. Assessment of the existing paint adhesion is important when overcoating is considered. ASTM D 3359 provides guidance for determining adhesion. These risk-mitigation measurements can be collected for specific bridges considered for maintenance activities, rather than collecting the information on a system-wide basis.

Also important in the evaluation of aged coatings as candidates for overcoating is the "condition" of the existing coating film itself. The currently available guidelines do not sufficiently quantify this parameter, but it is considered important and is a key qualitative factor used by coatings inspectors, consultants, and specifiers when assessing overcoating risk associated with a particular structure. Briefly, this qualitative factor describes the "life" remaining in an aged paint film as observed during the destructive testing for adhesion testing. Aged alkyd coatings tend to deteriorate from the "outside-in" through oxidation. Over the years this can produce a coating that is still functional as a surface corrosion inhibitor, but a film that has low adhesion as well as low film cohesion. As a practical measure, if the coating "crumbles" at the leading edge of the blade used to cut through it during the adhesion test, it is showing signs of oxidation and lack of film cohesive strength. As such it would present an increased risk as an overcoating candidate since a new, cohesive paint film is being applied over an aged film with poor cohesion. Such an assessment is practical when considering specific bridges.

The literature also includes a number of other approaches that have been attempted to manage and evaluate the condition of coatings systems on bridges. An artificial intelligence model (AIM) has been developed for identification and tracking of bridge conditions [20]. The AIM utilizes an intelligent computer program to analyze digital pictures of a defect area to precisely determine deterioration rates. The AIM has three components. The first component is image processing which defines the image as the distribution and intensity of light in two dimensions. Second, the artificial neural networks are applied to analyze the data. Once the artificial networks are developed, the last step is to apply a hybrid model that identifies defects on the image [22]. Such an approach is relatively unproven, extremely costly and involved, and likely could not be implemented practically for a bridge inventory. Although representative of contemporary research, the approach is impractical for large structures and benefits to justify the cost and complexity of the approach are unlikely to be found.

3.3.2 Methods based on Determination of Deterioration Rates

Determining coating system deterioration rates is intended to evaluate or predict the future performance of a steel bridge coating, based on the historical performance of similar systems or a probabilistic estimate of the likelihood of deterioration. There are several methods that have been used for determining or estimating the corrosion rate of steel bridge coating systems including the Markov Chains, Weibull Distribution and Regression Analysis. The Markov chain method provides a probabilistic model of future deterioration based on Markov chain theory, and this is the deterioration modeling approach taken in the PONTIS bridge management software used by some states to program future maintenance and rehabilitation needs. Weibull distribution functions are frequently used to estimate the probability of failure over time for components and materials that have wear-out characteristics, i.e. increasing failure rates as a function of service life. This is a probabilistic approach that can be utilized to estimate risks over specific time periods, and is most useful when a large number of samples of similar characteristics and operational environments are available. Regression analysis is a deterministic method to evaluate the deterioration pattern based on previous performance by fitting a polynomial function to performance data over time. Regression analysis can be the most straight-forward of these methods for characterizing the deterioration of a coating system; however, it requires existing data on system performance over time that is not typically available.

These approaches to deterioration modeling are briefly reviewed herein to provide some context on available technologies with potential to be applied for coatings maintenance in the future. However, it should be noted that the results of the field survey did not indicate that such approaches to estimating future deterioration rates were likely to be beneficial in the near term for managing coatings across the present inventory. Given the variations in coatings, maintenance practices, and limitations of available data across the inventory, these approaches may be more useful in the longer-term, once suitable data is available through strategic condition assessment of coatings.

3.3.3 Markov Chains Method [23]

The Markov chains model has been used [23] for prediction of future performance of bridge coating conditions. This probabilistic method is applied to estimate future bridge coating conditions, based on the current condition state and the probability that the coating will deteriorate to the next lower condition state in the future. Markov chains is a widely used approach because it can efficiently estimate the future conditions based on certain transition probabilities selected. The transition probabilities describe the likelihood that a coating or system will change condition state during a given period of time. The method is based on estimating different periods of time in particular condition state to estimate the future performance. The limitation of the method is that it typically does not consider the time that a particular item has already been in the current condition state, which is typically an important factor is estimating the future behavior.

The essence of the Markov chain approach is to develop a matrix of transition probabilities that express the likelihood of a coating to transition from one condition state to another in a given period of time, for example, over a 4 year period. This transition matrix has the form:

$$P = \begin{bmatrix} p(1) & q(1) & 0 & 0 & 0 \\ 0 & p(2) & q(2) & 0 & 0 \\ 0 & 0 & p(3) & q(3) & 0 \\ 0 & 0 & 0 & p(4) & q(4) \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Where *p(j)* is the probability of the bridge coating staying in condition *j* during one duty cycle, and *q(j) = 1 – p(j)* is the probability of the coating moving down to the next state (*j+1*). Based on this model, the future performance of the coating system can be predicted using the equation:

$$S(n) = S(0) \cdot P^n$$

Where S(n) is the state vector at duty cycle *n*, and S(0) is the initial state vector (the initial condition of the coating).

In a Markov chain model, it is assumed that the future condition depends only on the current condition state, not the previous condition states or time in the current condition state. In the literature reviewed, it was reported that the transition probability matrix was determined based on a deterministic regression model, in other words, based on historical performance of coatings systems in the state. Results of the study indicated that the Markov chain model matched closely the regression analysis. Given the variability in performance of coatings in the field, and the dependence of performance on the quality of application of the coating and localized environments such as leaking joints, the additional complexity of applying Markov chains seems inappropriate at this time. In the future, if deterministic methods of predicting future performance prove invalid, pursuing such probabilistic methodologies may be justified. Given the sparseness of reliable historical data on coatings performance in Missouri, the construction of either Markov chain models or original regression analysis appears infeasible at this time. However, the data from the regression analysis can be used as a starting point for estimating the expected life of coatings in general terms, which can be adjusted and modified to accommodate environmental conditions, effect of coating location (such as beneath bearings) and other factors that may affect the estimated life of a coating system.

3.3.4 Regression Analysis

Regression analysis is a deterministic method, that attempts to fit a polynomial curve to best match historical data on the performance of a coating, as a means of estimating the future performance. Climate, age, traffic and environmental factors affect the condition and deterioration rates of bridge coatings [23]. In the regression analysis reviewed in the literature, these factors were found to not have a corollary effect on the regression model, and polynomial terms based only on the age of the coating were used to develop an estimate of future performance of coatings. Slightly different polynomial terms were determined for different paint systems (Lead-based and zinc/ vinyl) and Interstate roads vs. State routes in Indiana. Although the rates of deterioration varied slightly between the different polynomials identified, the overall deterioration characteristics varied only slightly, between ~26.5 and 31.5 years of total life depending on the specific coating system and the road system. Figure 3.1 shows the polynomial curves for interstate bridges developed through the study. A typical polynomial developed in the research, for zinc/vinyl coatings, is shown below. Note that this polynomial depends only on the age of the coating, and does not include environmental effects:

$$Paint\ rating = 9.06 - 0.201 \cdot Age + 0.0103 \cdot Age^2 - .000348 \cdot Age^3$$

In this research, the condition rating of 5 can be estimated as the failure of the coating. For the polynomial listed above, the time period from a condition rating of 9 to a condition rating of 5 can be estimated in years. The research also presented the Markov approach to estimating the future deterioration of the coating, however, the results of this much more complicated analysis were not different than the regression analysis. Such a polynomial deterioration curve could be applied for estimating the remaining life of a coating in the MoDOT inventory using a spreadsheet program. However, it should be noted that such polynomial deterioration data based on regression analysis is very general, and should not be expected to predict effectively the future performance of any given bridge. This is a primary obstacle to using such data: it represents the population, but not the particular bridge. An analogy for this effect can be found in the insurance industry: insurers can predict with great precision the number of people that will be killed in automobile accidents in a given year, but cannot determine if any specific person will be killed. In terms of bridge coatings, such an approach may provide broad guidance of the number of coating projects likely in a given year, but could not predict the needs of any particular bridge effectively.

It may be just as valid to assume a linear or bi-linear deterioration curve, and make gross adjustments based on subjective/qualitative data such as experience and knowledge of generic operational characteristics. For example, a combination of the deck rating and knowledge of the local environment severity (such as end-joints or deck drains) could be used to estimate the remaining life of a coating based on existing conditions. It should be noted that the given polynomial essentially states that the coatings are assumed to drop one condition state every 5 years, with a slight increase in later life of the coating, resulting in a service life for the coating of approximately 25 to 30 years. However, the dependence of this lifetime prediction on the drainage characteristics of the structure and interventions (over-coating or spot painting) make the implementation of longer-term predictions problematic.

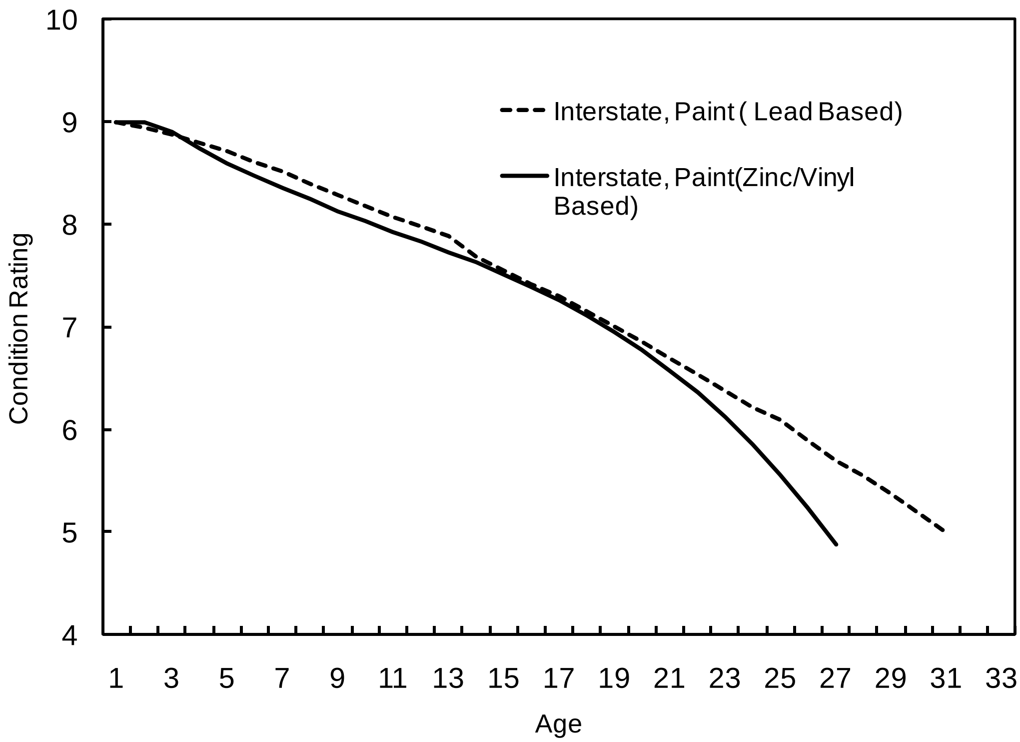


Figure 3.1 Deterioration Curve for Highway Bridge Coatings Based on Regressions Analysis.

3.3.5 Transportation Management System (TMS) Data

The existing database of information regarding coating systems in Missouri was collected from the TMS database. A tabular summary of key data from the TMS related to coating systems was provided to the researchers by MoDOT forces. The TMS database is used to store a number of different key MoDOT data, including the information stemming from bridge inspections. Data from bridge inspections typically includes the data to satisify the national bridge inspection standards (NBIS), which includes the ratings for key components of a bridge, the superstructure, substructure and deck, as well as a variety of other data regarding the condition of particular bridges. Among the data included in the bridge files is a series of notes and associated fields that included data on the coating systems for bridges. A listing of the steel bridges in Missouri was obtained that included data on the coatings systems for bridges that is included in the TMS database. This data provides information on the original coating systems on bridges, recoating operations that have occurred historically, and condition ratings for the coatings that have been provided by bridge inspectors conducting biennial inspections. It is known that this data is in some cases inaccurate or incomplete. However, the data represents the current state of compiled data on coating systems currently available, and can provide some insight into either the current condition of coating and/or needs for improving the currently available data. This might include things like establishing more formal procedures for the collection of data, uniform procedures for rating coating, and improving data input reporting coatings operations in Missouri.

There are a total of 4561 bridges shown in the database. This section provides an overview of the analysis done on the TMS data to provide context for the field analysis of bridge coatings. Data included suggests that the majority of bridge coating systems in Missouri have been rated in the fair to good range, a typical result for subjective rating systems that have a tendency toward moderate ratings within a given range. Table 3.1 shows the distribution of ratings in the database for steel bridges in Missouri. As shown in the table, more than 80% of the bridges in Missouri have ratings of fair or good for the coating.

Table 3.1 Condition Ratings of Bridge Coatings in the TMS Database.

Condition	No of bridges	Percentage
Excellent	84	2 %
Very good	159	3 %
Good	2454	54 %
Fair	1349	30 %
Poor	361	8 %
Very Poor	47	1 %
Unrated	107	2 %

The original paint system used is indicated in the database, and is shown in Table 3.2. This data shows that more than half of the bridges in the database do not have their original paint system indicated. It also indicates that approximately a quarter of the bridges have lead-based coating, which will present environmental challenges if recoating of the bridges is selected as a maintenance action for the bridge.

Bridges that have had repainting activities, either by department forces or by contractors is also included in the database, and it indicates department repainting activities for 2387, or 52% of the bridges in the database. Contract repainting was reported for a much smaller number, 575, of the bridges. The primary systems used for contract repainting (historically based on the TMS data) is Systems S, B and G system. Among the department repaint jobs, System S is the primary recoating system used and is the current practice, system C and G were also indicated.

To get an overall view of the existing paint inventory in Missouri, a graph of Age versus Condition Rating was plotted from the data in the TMS database, which helps to illuminate some issues with the existing condition ratings and for predicting future coating performance (see Figure 3.2). Namely, there are no easily observable trends that relate the age of the coating and the condition rating. The Age was calculated by subtracting the current year to the most recent repaint on that bridge, and the condition ratings provided in the TMS were mapped to numerical ratings to simplify analysis.

Table 3.2 Original Paint Systems Listed in the TMS Database.

System Type	**Definition**	**No. Of Bridges**
A System	Red lead/Brown lead/Aluminum	1041
B System	Red basic lead silico-chromate Brown basic lead silico-chromate Aluminum or Green basic lead silico-chromate	520
C System	Two-component inorganic zinc silicate primer, Aluminum or Green vinyl finish coat	299
D System	Waterborne inorganic zinc silicate primer, Aluminum or Green Vinyl Finish Coat (for field application)	5
E System	Waterborne inorganic zinc silicate primer (two coat system for shop application w/ no overcoat)	6
F System	High solids inorganic zinc silicate primer, green or gray tint (no top coat)	26
G System	High Solids inorganic zinc silicate primer, green or gray tint, epoxy primer (in color of top coat), Aliphatic acrylic high gloss polyurethane finish coat, green or gray	177
H System	Three-component high solids inorganic zinc silicate primer, Acrylic intermediate coat, to provide contrast, Acrylic finish coat, green or gray (typically used in 300045 brown for weathering steel at expansion devices)	30
S System	Calcium sulphonate (penetrating sealer, primer, topcoat)	26
Misc. listing		50
Total		**2180**
Original Coating not recorded		**2381**

Such dispersion of data is common for bridge inventory condition data, due to the stochastic nature of deterioration patterns common to bridges, the subjective nature of the rating systems, and the ongoing nature of maintenance activities that can influence the rating. Additionally, in the case of the TMS data, the condition data for the coating system may not be representative of the current condition due to historical limitations on data entry. Based on the field survey, this may be made more complicated by maintenance coating activities that address aesthetic needs for a bridge coating, i.e. painting the worst portions of the facia girders to maintain appearance until more comprehensive maintenance/repair can be achieved.

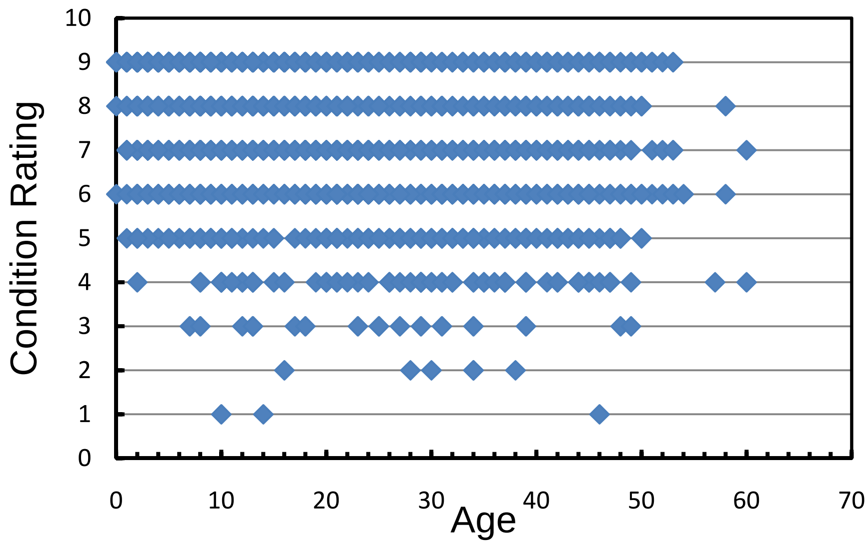


Figure 3.2 TMS Condition Data for Coatings in Missouri.

3.4 Condition Rating System

As noted previously, one limitation faced in assessing the condition of coatings overall in Missouri are the current limitations of the condition assessment scheme used by inspectors to record the condition of coatings during routing bridge inspections. Utilizing a consistent methodology to assess and record the condition of a coating would provide critical data for decision making, both on a project and system level. Implementing a uniform condition assessment methodology with appropriate tools to relate the condition assessment to maintenance and repair needs would greatly improve the data available to decision makers. To address this need, guidelines have been developed to assist in the consistent evaluation of the coating in the field. These guidelines consist of specific guidance on rating coatings according to a 5-level condition state description that is strategically defined to assist in indentifying coating systems for which touch-up, over-coating or re-coating are viable options based on the current condition of the coatings. The visual guide is intended to provide a guide to inspectors for rating bridge in the MoDOT inventory. The overall approach of the guide is to rate a bridge coating condition for two portions of the bridge, the portion of the bridge at the beam ends and the mid portion of the bridge beam.

The rating system suggested corresponds to the current MoDOT rating system and according to SSPC scales. A number of different rating schemes were considered during the research, including using a reduced number of rating levels to simplify the ratings and make it more likely that an inspector would select ratings consistently. However, after the initial portions of the field survey were completed, it was apparent that there was not a strong need to change the levels substantially from what is currently considered by inspectors. In fact, the levels used are likely to have programmatic value in describing the conditions for which intervention may be a cost-saving option. However, the analysis of the TMS data and initial survey results showed that these ratings were sometimes not being used in the field, not being used consistently, or the results of the inspection were not being updated into the TMS database. Therefore, it was deemed more useful to maintain the established SSPC scales generally, but to add text descriptions to aid the inspector as well as visual examples to help guide the inspector on the application of the ratings. These condition state descriptions are coupled to a comprehensive visual guide that shows photographic illustrations of coatings conditions in the field and their appropriate ratings, to enable consistency in the evaluations moving forward. It is believed this is the most comprehensive guide developed to date in the U.S. for the evaluation of the bridge coating conditions in the field.

The rating system includes a 5 rating scale, including condition ratings of Very Good, Good, Fair, Poor and Very Poor, as shown in Table 3.3. The Very Good rating is intended to capture the initial conditions following a recoating or overcoating (or a new coating system), when the coating is in like-new condition. The Good rating is intended to characterize those coatings for which work is not needed, but rusting has initiated at a minor level. The Fair rating is intended to characterize a coating that is a good candidate for touch-up or selected overcoating, while the rusting is still at levels of less than 1%. This rating (Fair) is essentially an on-deck rating, indicating that the deterioration has initiated and can be expected to advance to requiring recoating or overcoating in the next 5-10 yr interval. The Poor rating is intended to characterize those coatings for which overcoating is a viable option, and recoating may not yet be required. This rating can help identify those bridges for which contemporary action is needed to stem deterioration and avoid recoating. Finally, the Very Poor rating is intended to characterize coatings in advanced stages of deterioration such that substantial repair/recoating is required, and rusting is >10%. Although some states currently may consider overcoating when rust levels are as high as 20% of the surface area, especially when the existing coating system is lead-based, typically rusting over more than 10% of the surface is usually considered a limitation for effective overcoating.

Although the suggested rating levels may correspond to possible repair strategies, it is not the intention of the guide that the inspector be assessing the possible repair strategies independently. Rather, the levels are intended to characterize the conditions of the coating at the bridge such that the evaluation of possible repair strategies can be accomplished by project-level decision makers, using the data from the inspection. The rating levels also reflect the existing deterioration rate data that was available in the literature, which reflect a 5-10 year life once a "Fair" rating is obtained. This will naturally be effected by the conditions at the specific bridge, but the separation of ratings for the mid-span and beam-end should provide some insight in general, with beam-ends expected to be closer to the 5 year life and mid-span, in the absence of drainage from the deck onto the structure, to have 10+ yr of remaining life. Once data according to the revised scoring scheme has been collected and documented for the majority of bridges in Missouri, estimation of future coating needs can be easily developed through relatively simple deterministic methods based on the location of the damage (mid-span or beam-end), the likely drainage characteristics at the bridge, and the current rating. A simple spreadsheet program should be suitable for this application. Since each bridge is inspected at least every 24 months, this data should only take a couple of years to develop fully.

3.4.1 Condition Assessment Methodology

In this revised scoring scheme, the intent is to provide two separate scores for the bridge coating – one rating for the mid-span of the bridge, and one rating for the end-span. Guidance for using the rating scales are as follows:

- The rating should be applied based on the coating condition for primary members.
- The rating scale is appropriately applied when it represents the overall condition of the member sections being rated. A separate rating should be applied for the mid-span sections of the bridge and beam ends.
    - "Beam ends" are those section of the primary member located < 12 ft. from the end of the beam, where the effects of the joint leakage are anticipated (see Figure 3.3).
    - "Mid-span" are those sections of the bridge beam located between the "beam ends" (> 12 ft. from the beam ends.)

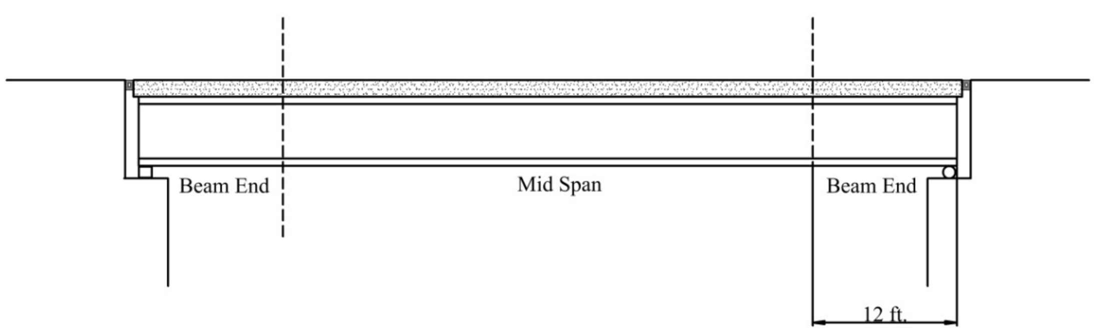


Figure 3.3 Schematic Diagram Showing Mid-span and Beam-ends.

- Beam end conditions may be significantly different under certain conditions due to variations in the expansion device performance and/or drainage characteristics of the bridge. In this case, rate the beam-end with the lower rating. For example: A bridge runs east to west on a vertical slope such that the east side is higher than the west side, resulting in deck drainage at the west side. The beam-ends on the west side are in poor condition while the beam-end on the east side are in good condition. Rate the beam ends as poor. *Rationale: The condition assessment should capture the urgency of action, such that decision and predictions can be made based on the ratings. The fact that only the west-end is in poor condition affects the quantity of repair needed, but not the urgency of repair needed. As such, the beam-end in the worst condition needs to be rated.*
- The ratings are improperly used if they attempt to describe a localized or nominally occurring instance of deterioration. For multi-beam structures, the rating should capture the overall condition of the members at mid-span and the beam-ends. *Rationale: Localized areas of deterioration are not uncommon for bridges, but typically do not reflect the urgency of a maintenance action, since the damage is localized. If such localized damage results in significant section loss, this is a structural condition that should be noted appropriately.*
- The extent of section loss for a steel member is a structural condition, and should not influence the rating of the coating itself. Section loss should be noted appropriately in the inspection results for the component.
- Peeling of paint: Paint peeling is an aesthetic condition that may not represent the effectiveness of a coating system for corrosion protection. Rating of the coating system is intended to represent the extent of corrosion (rust) that indicates the corrosion protection characteristics of the coating is compromised, and to what extent. If ratings based on peeling of paint are needed, they should be separated from the rusting evaluation (a separate TMS field). Suggested ratings for peeling would by Good (<10%), Fair (10% - 30%) and poor(>30%).

Table 3.3 Proposed Rating Scale for Coating Condition Evaluation.

Rating	Description
Very Good	Perfect, new condition. The coating is a new coating system with very little or no damage. This condition correlates to the SSPC rating 10, less than 0.01 % rust and SSPC-9 (Greater than 0.01 up to 0.03%).
Good	Some very minor corrosion. The coating system is in good condition, with little overall corrosion/rust corresponding to SSPC 8 (greater than 0.03 and up to 0.1 %).
Fair	The coating has observable damage corresponding to SSPC-7 (greater than 0.1 and up to 0.3 %) to SSPC-6 (Greater than 0.3% up to 1%).
Poor	The coating has widespread corrosion corresponding to SSPC-5(Greater 1% up to 3%) to SSPC-4 (Greater than 3% up to 10%).
Very Poor	The coating system is in advanced stages of deterioration, with greater than 10% rust corresponding to SSPC-3 or less.

3.4.2 Discussion of Ratings Rules

The rating rules are intended to provide suitable information to generally describe the overall condition of the coating in the mid-span and beam-ends for a given bridge. It is normal practice, and typical under the NBI, to provide ratings that describe the overall condition for the purposes of assessing the general condition of a component. Element level inspection systems, like those used for PONTIS and other bridge management systems, provide more detailed inspection data that includes an assessment of specific quantities of damage/deterioration. This data could be collected and provide more detail, but would not be consistent with the overall approach used for inspections in Missouri, which conform to the NBIS requirements. If, in the future, the overall inspection program moved toward an element-level system, these guidelines could be easily adjusted to match that philosophy.

For some states, a span by span rating system is used, in which the worst element in each span is rated. This approach is based on the philosophy that the inspection should identify potential safety issues that may be localized in nature. As such, the worst element within each span is rated. This data is then converted to match NBIS requirements. Applying such a philosophy to coating inspection would provide better detail on the extent of damage to the coating system at specific bridges, however, would again not be consistent with the overall approach currently used in Missouri.

However, rating of the beam-ends as suggested here does adapt the philosophy that the worst beam-end condition should be reported. Based on the field survey, multi-span simply supported structures frequently have common condition characteristics at the beam ends. In some cases these beam ends may have very different conditions, if, for example, the drainage on the bridge is such that one beam end is exposed to very little run-off from the deck while another beam end is exposed to significant run-off from the deck. In such a case, one beam-end may have a general condition of “good” while the other has a general condition of “poor.” In such cases, inspector may assign a condition rating of “Fair.” We feel that the appropriate rating for the condition is “poor,” and as such have included the direction that the worst beam-end be reported, such that the rating suggests accurately the need for maintenance painting (overcoating) to improve corrosion protection at the bearing area, where section loss is a typical, though sometimes localized to the beam end, damage mode.

Figure 3.4 Visual Guide Photos Showing Facia Girder Mid-span, End-span and Macro Photograph.

3.4.3 Visual Guide

To support the descriptive ratings of the condition ratings, a visual guide was prepared for use by inspectors. The visual guide is based in general on the SSPC visual guides, but is intended to provide a visual scale that is suitable for highway bridges. The guide is intended to assist inspectors with choosing the appropriate rating for the mid-span and beam ends. The guide generally provides a combination of the elevation views, interior span views and close-up views for each rating to assist in the rating of the bridge. The photographs are intended to show the bridge from the inspector's typical perspective, commonly taken from a location near the bridge abutment. The visual guide is included in Appendix A.

The guide consists generally of standardized photographs of different portions of a bridge structure that meet the subject rating guidance. For example, for the condition rating of “good,” photographs are shown that include an elevation of the facia girder and an elevation of the beam-end facia girder, as shown in Figure 3.4. Additional photos shows the interior characteristics, showing mid-span and beam ends for the interior sections as shown in Figure 3.5. The intention of the guide is to provide context for the inspector evaluating a given bridge to improve the reliability (i.e. consistency) of the condition ratings. This is common practice for visual inspection techniques, either for coating evaluation or other forms of deterioration. Because the rating scales are inherently subjective and therefore subject to interpretation by the inspector, the photos should assist the inspectors in making more consistent evaluations.

When comparing the overall ratings to those suggested in the SSPC/ASTM guidelines, the estimates of the percentage of area of rust must be based on the overall condition of the coating within the subject areas of the bridge (mid-span or beam end). Given the large scale of a typical bridge, this can be significantly more challenging than evaluating, for example, a small steel component in the yard. Macro photos showing a close-up view of the typical damage (rust) level for the given rating will provide additional context for the inspector that will help to more consistently assigned suitable ratings for the bridge.

The visual guide developed is intended to provide a full-sized field notebook that includes examples for a variety of coating systems and example scenarios or conditions. This guide is suitable for office use or as a reference kept with inspection equipment in a vehicle. The visual guide is included in Appendix A. In this appendix, example images are shown for each condition from very good to very poor. Images of the beam-end and mid-span are shown for exterior (fascia) girders and interior girders. These photographs are taken showing the gross areas of the bridge from the perspective that an inspector would have when inspecting the bridge during a typical routine inspection. The visual guide also includes close-up images that are intended to represent typical localized deterioration that would be present at the bridge, for each of the condition states.

Figure 3.5 Example Photograph for Interior Sections of a Bridge with Coatings in Very Poor Condition.

A small, pocket-sized guide that can be easily carried in the field has also been developed. The pocket guide is modeled on a number of typical field evaluation guides used for highways or other industries, such as the Applied Technology Council (ATC) pocket guide for Post-earthquake Safety Evaluation of Buildings. This pocket guide includes a subset of images from the visual guide for easy reference in the field. This field guide includes the relevant data for the different rating conditions, example photographs of the bridge superstructure and detailed images of the mid-span and beam ends. For each rating, the draft field manual includes five images; a large, overall photograph of a bridge, and four more detailed (close-up) photographs showing beam-ends, mid-span and a macro photograph. The field notebook has been developed and was used for coating evaluations in the field. A photograph of the draft field pocket guide is shown in Figure 3.6. The pocket guide is included in Appendix B.

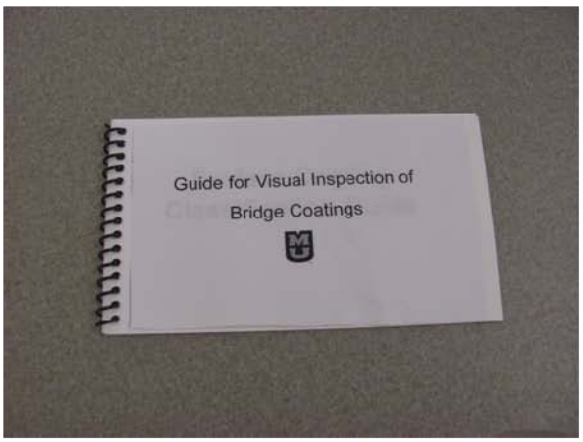


Figure 3.6 Photograph of the Field Pocket Guide for Evaluating Coatings.

3.4.4 Testing of Rating Scales

The subjective rating scales to be utilized for rating bridge coatings can be tested to evaluate the consistency, or reliability, of inspector evaluations. Such testing develops statistical data on the inspector's ability to make effective ratings, which depends typically both on the inspectors characteristics (training, experience and knowledge of the rating scale) and the effectiveness of the visual examples. To facilitate this testing, sample sets of photographs indicating the 5 ratings were prepared. To test the samples, both hard-copy and electronic files were prepared. The electronic files could be transmitted to an inspector via email in a file with the order of the samples randomly mixed, the inspector simply reorders the samples within powerpoint and returns them to the researchers for scoring. The process is shown schematically in Figure 3.7. In this figure, visual examples of the 5 ratings are shown out of order on the left, and correctly ordered on the right. This is a very simple and time-effective approach for testing the effectiveness of the visual guides. Hard copies are also being produced for similar evaluation, and can be used in the future for training of inspectors. Maintaining such resources will allow the condition rating system to be applied consistently over time, as personnel conducting the inspections change.

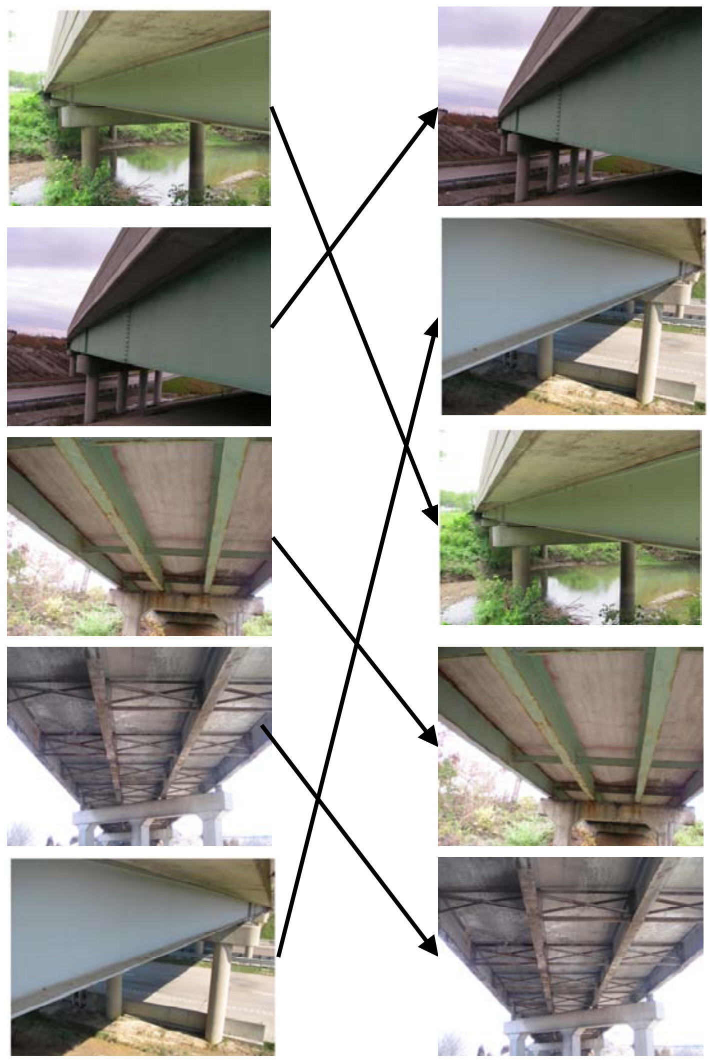


Figure 3.7 Example of Re-ordering Visual Samples for Coating Ratings.

Sets of images showing the conditions of beam-ends and mid-span conditions for fascia girders and interior girders, as well as close-up (macro) photographs of coatings in each of the five conditions states were developed for testing. Directions for sorting the images according to their relative conditions were developed. These 5 sets of images and associated directions were transmitted to an inspector pool that included 5 MoDOT bridge inspectors and a coatings consultant for assessment. During this testing, the inspectors were able to sort the macro photographs without error, with each inspector returning the images in the correct order. Overall, 3 of the MoDOT inspectors were able to sort the images without errors for all 5 sets of image. Table 3.4 shows the overall results for the testing. As shown in the figure, incorrect answers were more likely to occur in the Good-Fair-Poor ratings than in the Very Good or Very

Poor ratings. This is not surprising, since the limits of the rating scale (Very Good and Very Poor) are typically more readily recognized than more subtle distinctions between coatings in the Good-Fair-Poor range. Overall, the error rate for sorting the images was 13%, or 19 errors in 150 different possible categorizations.

Table 3.4 Results of Testing for Coating Condition Images.

Images	Very Good or Very Poor Incorrect (%)	Good to Poor Incorrect (%)	Overall Incorrect (%)
Fascia Girders, Mid-Span	8	28	20
Fascia Girders, Beam-End	0	33	20
Interior Beams, Mid-Span	17	17	16
Interior Beams, Beam-Ends	0	11	6
Close-up (Macro)	0	0	0
All Sets	5	18	13

4. FIELD SURVEY

This section of the report describes the results of the field survey of coatings conditions in Missouri. In total, 96 bridges have been inspected across 10 MoDOT districts and 26 counties. Mapped locations of steel bridges were obtained from MoDOT to locate the bridges in the field. Field surveys were conducted by traveling to the bridge locations and obtaining photographs of the condition of the paint systems. A standard set of photographs showing beam ends, fascia girders, and interior girders were obtained from the structures. Dry film thickness (DFT) measurements were made on some bridges. The coatings conditions were evaluated according to a visual guide developed as part of the research task. This visual guide provided a subjective, 5-level rating system for the coating ranging from very good to very poor, as described previously in the report. The coating systems were rated for end-span condition (at the bearing area) and mid-span conditions, and an overall rating for the coating system was also determined. These ratings were compared with the existing ratings available in the TMS database. All inspection results and associated photographs were configured into a document for review.

4.1 System S and G Condition

The current typical practice in Missouri is to overcoat bridges with System S coating, and to recoat bridges with System G, and in some cases, use zone painting with system G at the beam ends. System G coatings are typically specified for new bridges. The field study focused on assessing these coatings systems to assess the condition of these contemporary coating systems. 60 bridges with System S and System G were inspected in 26 counties. The results of the field survey were separated according to whether the coating system was greater than 5 years old or less than 5 years old. Coating systems showing poor performance after less than 5 years of service would generally be categorized as very poor performers. In summary, the system G coatings were all performing very well in the field, in most cases in very good condition. The system S coatings observed in the field had more scattered results, with a few cases of recently applied overcoatings having failed with less than 5 years of service. Based on the observations, these failures typically included peeling paint over existing coatings as well as active, widespread corrosion. It appeared that these early failures are the result of the limited surface preparation associated with the current overcoating practices, the severity of the deterioration that existed at the time of the overcoating, and continued exposure to drainage from the bridge deck.

The section below contains data from the field survey for the system S and G coatings.

Condition Summary of S System Bridges

There were a total of 44 System S coating evaluated in the field. This included 41 department recoating jobs, 1 contract recoating and 2 coatings that were unspecified in the TMS but appear to be department recoatings. There were 23 bridges where the coating system was applied in the last 5 years. The overall condition ratings for these bridges, which is typically driven by the beam-end conditions, showed that 74% of the coatings were in fair to good condition, while 26% were in poor or very poor condition. The TMS data on the coating condition ranged from fair to very good. This may reflect the somewhat rapid deterioration of the overcoatings, since the periodic inspections are conducted only every 24 months, and several of the coating systems appear to have deteriorated over a shorter time frame such that the most recent inspection may not have reflect the most recent deterioration. These may also be entries in the TMS that have not been updated.

Table 4.1 Data for System S Coatings with Less Than 5 Years of Service Life.

SYSTEM S					
Coating less than 5 years					
Bridge Number	**Paint Year**	**TMS Condition**	**End- Span Field Rating**	**Mid-Span Field Rating**	**Overall Field Rating**
A0048	2006	Good	Fair	Good	Fair
A0095	2006	Good	Good	Good	Good
A0491	2006	Good	Very Poor	Very Poor	Very Poor
A0491: Facia girders were in good condition, mid- span was in very poor condition, partially recoated, old system is not available.					
 					
A0557	2006	Good	Fair	Poor	Poor
A1256	2006	Fair	Fair	Fair	Fair
G0519	2006	Good	Fair	Good	Fair
L0928	2006	Good	Poor	Poor	Poor
L0928: One end of the facia girder was in good condition, the other end was in very poor condition. Partially recoated.					


S0352	2006	Good	Poor	Poor	Poor
A0025	2006	Good	Poor	Very Poor	Very Poor

A0025:End- span was in poor condition, mid-span was in very poor condition. Partially recoated.


T0561	2007	Good	Good	Good	Good
A1414	2006	Good	Good	Good	Good
A2551	2006	Good	Good	Good	Good
A3200	2006	Good	Fair	Fair	Fair
A1859	2006	Good	Fair	Good	Fair
N0983	2006	Good	Fair	Fair	Fair
N0447	2006	Good	Very Poor	Poor	Very Poor
R0568	2006	Good	Good	Fair	Fair
S0871	2007	Good	Good	Good	Good
A3292	2005	Very Good	Good	Good	Good
L0537	2006	Good	Good	Good	Good
N0348	2006	Good	Good	Good	Good
P0360	2007	Good	Fair	Fair	Fair
L0188	2008	Good	Fair	Fair	Fair

Condition Summary (Overall Rating)

Condition		**Numbers**	**Percentages**
Very Good		-	0%
Good		8	35%
Fair		9	39%
Poor		3	13%
Very Poor		3	13%
	Total:	23	100%

Among the bridges with system S coatings with less than 5 years of service life, there were cases where S system coatings had only been applied in the bearing areas or along accessible portions of the facia girder.

In this case, the condition of the coating system overall may not be indicative of the actual performance of the system S overcoating. These situations are noted in the table below if the portion of the structure that was actually overcoated did not match the general condition of the coating system.

Table 4.2 Data for System S Coatings with More Than 5 Years of Service Life.

SYSTEM S					
Coating more than 5 years					
Bridge Number	**Paint Year**	**TMS Condition**	**End- Span Field Rating**	**Mid-Span Field Rating**	**Overall Field Rating**
N0151	2004	Good	Good	Good	Good
A0096	2004	Fair	Fair	Good	Fair
P0838	2004	Good	Good	Good	Good
N0558	2003	Very Good	Fair	Fair	Fair
T0236	2000	Poor	Poor	Poor	Poor
A0748	2002	-	Good	Fair	Good
P0608	1997	Poor	Poor	Very Poor	Very Poor
A0558	2001	Fair	Poor	Very Poor	Very Poor
A1833	2000	Fair	Good	Poor	Fair
G0302	1996	Good	Good	Good	Good
A2341	2003	Good	Good	Good	Good
L0339	2003	Fair	Good	Good	Good
N0615	2003	Excellent	Very Poor	Very Poor	Very Poor
A0599	2001	Good	Very Good	Very Good	Very Good
L0697	2001	Fair	Good	Poor	Fair
L0773	2001	Good	Good	Good	Good
A1869	2000	Good	Good	Good	Good
A3080	2002	Good	Good	Good	Good
R0522	2002	Good	Good	Good	Good
R0523	2000	Good	Good	Fair	Fair
A0614	2004	Good	Good	Good	Good

Condition Summary (Overall Rating)		
Condition	**Numbers**	**Percentages**
Very Good	1	5%
Good	11	52%
Fair	5	24%
Poor	1	5%
Very Poor	3	14%
Total:	21	100%

There were 21 system S coating systems that were greater than 5 years old. For these coating systems, 57% were in good to very good condition, and a full 81% were at least in fair condition. The observations of these systems in the field showed that many of the systems are performing quite well beyond 5 years of service life. Although some of these systems were in poor to very poor condition after more than 5 years of service, the majority were not. Given that the recoating is typically applied to original coating systems that were already in poor condition, particularly at the beam ends, the data from the field evaluation suggests that the system S coatings are extending the service life of the coating systems effectively. The expected life for such an overcoating process is typically 10 to 15 years, and the field data suggests that this service life will be achieved in many cases.

When considered within the context that bridges with system S coating are less than 5 years old, the data suggests the overcoating process can be successful in extending the service life of the coatings. Based on observations in the field and discussion with experts, it would appear that the variations in the performance are likely related to a combination of the variations in the effectiveness of surface preparation and the severe damage that is present at the time of the over-coating. Figure 4.1 shows the coating conditions observed as a function of the time in service for the coatings. As shown in the figure, the age of the recoating does not appear to correlate with the condition of the coating, such that the condition of the recoating does not appear to be time-dependant, which further suggests that the condition is driven by factors such as surface preparation and localized environment.

Given that the expected service life of the over-coating can realistically be estimated in the range of 10 to 15 years, the data from the field evaluations indicates that this service life in many cases is being achieved, with isolated cases of early failures.

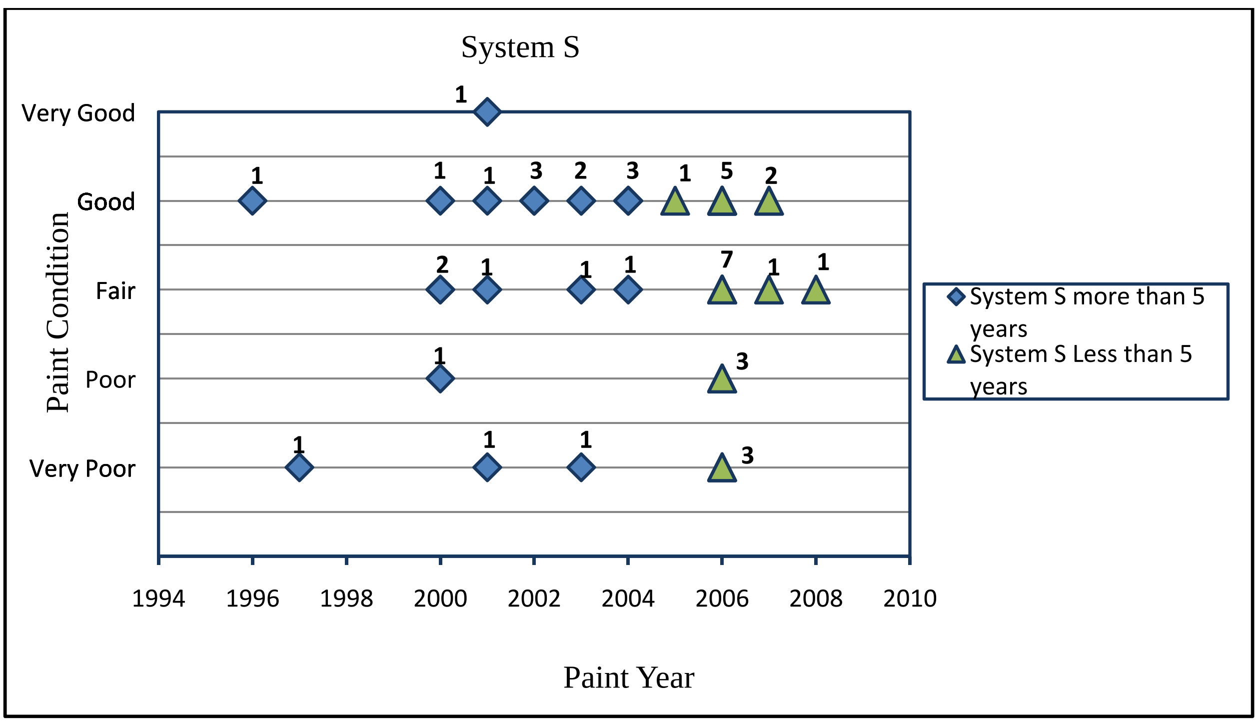
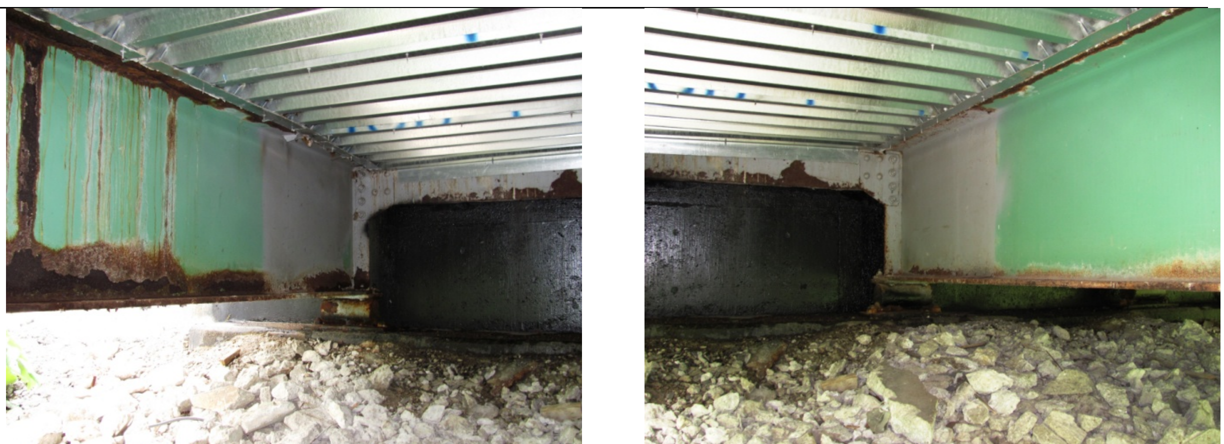


Figure 4.1 Summary of Conditions for System S Overcoatings.

An example of the over-coating with an early failure is shown in Figures 4.2 and 4.3 below. The photos below show zone painting, or limited over-coating by a maintenance crew.

Figure 4.2 Example of System S Coating with Early Failure, End-span of Facia Girder.



Interior end- span approxiamately 3 feet overcoated with System S

Figure 4.3 Example of a System S End-span Recoating at the Bearing Area with Early Failure.

Original paint was System C and fascia girders and end-span zone were painted with System S in 2006. Current condition of the end-span is rated as very poor since rust amount is more than 10%. This might result from inadequate adhesion between the existing coat and the new coating system. However, more likely it's a combination of limited mechanical surface cleaning resulting in corrosion and chlorides remaining on the surface of the steel, the continued exposure to aggressive wet-dry cycles from the leaking joint above. This combination of conditions results in an early over-coating failure. For this bridge, a deck renovation has likely improved the local environment and a second round of over-coating would likely perform much better. However, even with the renovated deck, the wet abutment face indicates that the expansion joint is leaking, which will result in reduced performance of an additional over-coating, though likely more localized in the bearing areas.

In contrast, Figure 4.4 below shows the fascia girders and beam-end for a bridge overcoated in 2006 with a beam-end rating of fair. Rust amount is less than 1%. This bridge shows good performance of the overcoat with regard to its condition rating. In this case the over-coating is performing well, though there is some rust-back beginning to appear in certain areas near the beam-ends where there is leakage from the expansion joint. In this case, a bridge deck renovation with prestressed panels and extended scuppers is successfully keeping deck drainage from the superstructure.

Overcoated facia girders

Figure 4.4 Example of System S Overcoating with Good Performance.

Overcoated end-span

Figure 4.5 Example of Interior Beam-ends with System S Overcoating.

4.2 Condition Summary of System G Bridges

16 System G bridges were evaluated in the field. According to the TMS database 12 System G bridges were the original coating, 2 contract recoating, 1 department recoating, 1 coating indicates contract repaint coincident with the year of construction, and 1 bridge is not available in the TMS.

There were 4 bridges that coating system is less than 5 years old. These 4 bridges were rated as very good condition as it is seen on the Table 4.3.

Table 4.3 Data for System G Coatings with Less Than 5 Years of Service Life.

SYSTEM G					
Coating less than 5 years					
Bridge Number	**Paint Year**	**TMS Condition**	**End- Span Field Rating**	**Mid-Span Field Rating**	**Overall Field Rating**
L0569	2007	Good	Good	Very Good	Very Good
A0172	2010	Poor	Very Good	Very Good	Very Good
A7123	2007	Good	Very Good	Very Good	Very Good
L0911	2009	Good	Very Good	Very Good	Very Good

Condition Summary (Overall Rating)		
Condition	**Numbers**	**Percentages**
Very Good	4	100%
Good	-	-
Fair	-	-
Poor	-	-
Very Poor	-	-
Total:	4	100%

12 System G bridges with coatings more than 5 years of service life were assessed. 100% of the coatings were in very good to good condition. The TMS data on the coating condition ranges from fair to very good which appears to be a lower rating than field rating assigned in the study. The oldest system G coating that was observed in the field had almost 15 years in service, and was in very good condition. This coating system had been applied to a jointless bridge with good deck drainage. The results of the survey are shown in Table 4.4.

Overall, all of the system G bridges observed were performing very well. This contemporary coating system has limited long-term historically data generally, because the system has come into common use in recent years. Therefore, their long-term performance in the field cannot be evaluated; the oldest coating system observed in this study was 14 years. However, the early-life data on these systems indicate that they are performing very well. Of course, the improvements in the durability design characteristics of modern bridges plays a role in this, as these modern bridges typically have greatly improved drainage characteristics relative to older structures. Figure 4.6 shows an example of the system G coating after 14 years of service life. The coating system, which includes some portion of a green topcoat, is in virtually perfect condition after 14 years of service life. The deck consists of prestressed panels, scuppers extended beyond the bottom flange, and the bridge is jointless.

Table 4.4 Data for System G Coatings with More Than 5 Years of Service Life.

SYSTEM G					
Coating more than 5 years					
Bridge Number	**Paint Year**	**TMS Condition**	**End- Span Field Rating**	**Mid-Span Field Rating**	**Overall Field Rating**
A6093	2003	Very Good	Very Good	Very Good	Very Good
A5863	2001	Good	Very Good	Very Good	Very Good
A5891	2001	Good	Very Good	Very Good	Very Good
A5977	2003	Very Good	Very Good	Very Good	Very Good
A5992	2003	-	Very Good	Very Good	Very Good
A5993	2003	-	Very Good	Very Good	Very Good
A5477	1996	Good	Very Good	Very Good	Very Good
A6289	2003	Very Good	-	-	Good
A6048	2001	Very Good	Very Good	Very Good	Very Good
A6052	2002	Very Good	Very Good	Very Good	Very Good
A0602	1998	Fair	Good	Good	Good
A6065	2001	Good	Very Good	Very Good	Very Good

Condition Summary (Overall Rating)			
Condition		**Numbers**	**Percentages**
Very Good		10	83%
Good		2	17%
Fair		-	-
Poor		-	-
Very Poor		-	-
	Total:	12	100

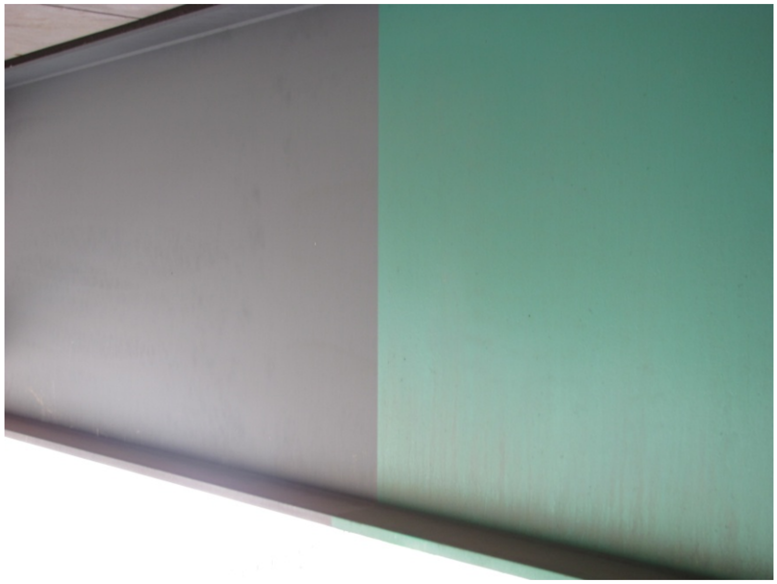


Figure 4.6 Example of 14-year-old System G Coating.

4.3 Condition Summary of System A, System B, System C Bridges

A total 8 System A, 9 System B and 16 System C coatings were evaluated in the field. All coating types had experienced more than 5 years of service life, since these systems are not contemporary coating systems. Among these coating systems, some were indicated as having repainting operations at some point in their service lives, while others were indicated as being original paint systems with no repainting operation indicated. For the summary of conditions indicated below, the coating systems were treated uniformly based on the repainting system or original system, where data was available.

Approximately 50% of the System A coatings were in fair to good condition, and 50% were in poor to very poor condition. The system A coating, which included lead, typically have more than 35 years of service life, since the use of these coatings were discontinued due to health concerns. In a few cases, these coatings were listed as the original paint system applied in the 1990's, which seems unlikely given the history of coating systems in the United States. For the system A bridges (see Table 4.5), several of which had more than 40 years in service, the structures that exhibited poor or very poor mid-span condition also had decks that were in advanced stages of deterioration, resulting in water passing through the deck, and/or deck drainage directly onto the superstructure.

Table 4.5 Data for System A Coatings with More Than 5 Years of Service Life.

SYSTEM A					
Coating more than 5 years					
Bridge Number	**Paint Year**	**TMS Condition**	**End- Span Field Rating**	**Mid-Span Field Rating**	**Overall Field Rating**
R0638	1967	Fair	Poor	Poor	Poor
L0899[1]	1998	Good	Good	Good	Good
T0818	1975	Poor	Very Poor	Very Poor	Very Poor
A1899	1972	Fair	Fair	Fair	Fair
N0984[2]	1990	Fair	-	-	Very Poor
R0607	1967	Fair	Poor	Fair	Poor
A1691	1967	Fair	Fair	Good	Fair
A2946	1976	Good	Good	Good	Good

Condition Summary (Overall Rating)			
Condition		**Numbers**	**Percentages**
Very Good		-	-
Good		2	25%
Fair		2	25%
Poor		2	25%
Very Poor		2	25%
	Total:	8	100%

[1] TMS listed system A, field label indicates Al-S

[2] Pile, recoated.

An example of the deck drainage issue is shown in Figure 4.7 that shows a System A coating after 35 years of service life. In this case, the deck drains primarily through deck drains on one side of the bridge. On the uphill side, where little drainage occurs, the coating system is in nearly pristine conditions after a little more than 35 years in service. On the other hand, on the downhill side where the primary deck drainage is occurring, the coating system is in advanced stages of deterioration and in very poor condition. As this Figure illustrates, the age in service of the coating has little relevance to its condition; the condition is driven primarily by the drainage patterns at the particular bridge.

Figure 4.7 Example of the Effects of Deck Drainage on Coating Condition.

A number of bridges with system B coatings on either the superstructure or pilings were evaluated. In total, 6 System B bridges and 3 pilings were inspected as shown in Table 4.6. The overall condition of the system B coatings is between fair and good overall. One bridge had a very poor condition rating for the end span, which was easily explained from the leaking joint at the end of the bridge. A second bridge had poor coating condition in the mid-span and very poor at the bearings. Again, the deck was in very poor condition for this bridge, leading to a breakdown of the coating system due to drainage from the bridge deck. With an average service life of greater than 25 years, the system B coatings are performing very well when not exposed to drainage from the deck and/or the deck is maintained in a good condition, such that drainage patterns in addition to those envisioned in the design stage were avoided. In other words the deterioration of the deck to a poor condition, leading to water passing through the deck onto the superstructure, appeared to be the direct cause of the coating failure.

There were 16 System C coatings evaluated in the field. All these coatings had more than 5 years of service life. 62% of System C coatings were rated Fair to Very Good, 38% rated Poor to Very Poor, as shown in Table 4.7. For the system C bridges, in every case where either the end span, mid span or both were in poor or very poor condition, the bridge deck was in poor condition.

Table 4.6 Data for System B Coatings.

SYSTEM B					
Bridge Number	**Paint Year**	**TMS Condition**	**End- Span Field Rating**	**Mid-Span Field Rating**	**Overall Field Rating**
A4415[1]	1986	Fair	-	-	Good
A4636	1988	Good	-	-	Good
L0119	1967	Poor	Very Poor	Fair	Poor
A3433	1978	Good	Fair	Good	Good
A4031	1987	Good	Fair	Good	Fair
A4034	1986	Good	Good	Good	Good
A4089	1987	Good	Good	Good	Good
A0548[1]	1984	Fair	-	-	Fair
S0604	1982	Poor	Very Poor	Poor	Very Poor

Condition Summary (Overall Rating)		
Condition	**Numbers**	**Percentages**
Very Good	-	-
Good	5	56%
Fair	2	22%
Poor	1	11%
Very Poor	1	11%
Total:	9	100%

[1]May be recoated

Table 4.7 Data for System C Coatings with More Than 5 Years of Service Life.

SYSTEM C					
Coating more than 5 years					
Bridge Number	**Paint Year**	**TMS Condition**	**End- Span Field Rating**	**Mid-Span Field Rating**	**Overall Field Rating**
G0544	1992	Fair	Poor	Good	Poor
A4709	1992	Good	Very Good	Very Good	Very Good
A2978	1999	Good	Good	Good	Good
X0108	1999	Fair	Very Poor	Very Poor	Very Poor
K0093	1998	Fair	Very Poor	Poor	Very Poor
K0094	1998	Fair	Very Poor	Very Poor	Very Poor
A4035	1994	Good	Good	Good	Good
A4091	1993	Good	Good	Good	Good
A4802	1989	Good	Good	Good	Good
A5110[1]	1994	Good	-	-	Good
L0200	1992	Good	Poor	Poor	Poor
L0908	1992	Good	Good	Good	Good
R0023	1992	Very Good	Poor	Fair	Poor
A4777	1991	Good	Good	Good	Good
X0759	1974	Fair	Poor	Good	Fair
A2476[2]	1974	Poor	Good	Good	Good

Condition Summary (Overall Rating)			
Condition		Numbers	Percentages
Very Good		1	6%
Good		8	50%
Fair		1	6%
Poor		3	19%
Very Poor		3	19%
	Total:	16	100%

[1]Piling, recoated, no data available on recoat
[2]Partially recoated

Table 4.8 shows a summary of the bridge deck drainage conditions for the system C bridges. As shown in the table, every bridge for which the deck drains onto the structure or the deck is in very poor condition, the coating system is in poor or very poor condition. The best performance of these coatings, which are approaching 20 years in service on average, is when the bridge is jointless.

Table 4.8 Drainage Conditions Observed for System C Coatings.

SYSTEM C			
Drainage Conditions			
Paint Year	**End- Span Field Rating**	**Mid-Span Field Rating**	**Deck Condition Notes**
1992	Poor	Good	Deck drains onto structure
1992	Very Good	Very Good	Scuppers, Deck in good condition
1999	Good	Good	Good deck drainage
1999	Very Poor	Very Poor	Deck in very poor condition
1998	Very Poor	Very Poor	Deck in very poor condition
1998	Very Poor	Very Poor	Deck in very poor condition
1994	Good	Good	SIP deck in good condition, jointless bridge
1993	Good	Good	Scuppers, jointless bridge design
1989	Good	Good	Jointless, deck in good condition
1992	Poor	Poor	Deck in very poor condition
1992	Good	Good	Jointless, Good deck condition
1992	Poor	Fair	Deck in very poor condition
1991	Good	Good	Scuppers, deck in good condition
1974	Good	Good	Deck in very poor condition
1971	Good	Poor	Deck in very poor condition

The positive performance characteristics of jointless bridges in terms of maintenance requirements for the bridge are well known, and this survey confirmed the service expectations for the coatings in jointless bridges. The addition of extended scuppers to below the bottom flange was also present in these high performing coating systems. The extension of deck scuppers to either below the bottom flange of the facia girder, or angled such that deck drainage is diverted away from the fascia, is having a very positive effect on the condition of the coatings in the mid-span of bridges.

The overall performance of the different original coating systems is shown in Figure 4.8. As shown in the figure, System G coatings are contemporary coatings that have had, so far in their service lives, very good performance in the field. Among the other systems that exist on the system, several are in poor or very poor condition. In each case, this degradation can be explained not by the service life of the coating, but by the drainage condition at the bridge as currently discussed. It should be noted that there are a number of original coating systems in the 30 to 40 years of service life range that are in fair to good condition. These bridges typically have very good drainage characteristics. Of course, what is missing from the data is the number of these older systems that have previously failed. The population of system A, B and C coating systems is somewhat skewed in terms of illustrating the overall performance of the coating systems since the time of their original application. Coating systems that have previously failed and have been replaced or overcoated are no longer available for evaluation, and therefore the coating systems failures are not included in the available population. However, among those systems that are available, it is clear that the most important factors in the performance of the systems are the drainage condition at the beam-end and the deck condition.

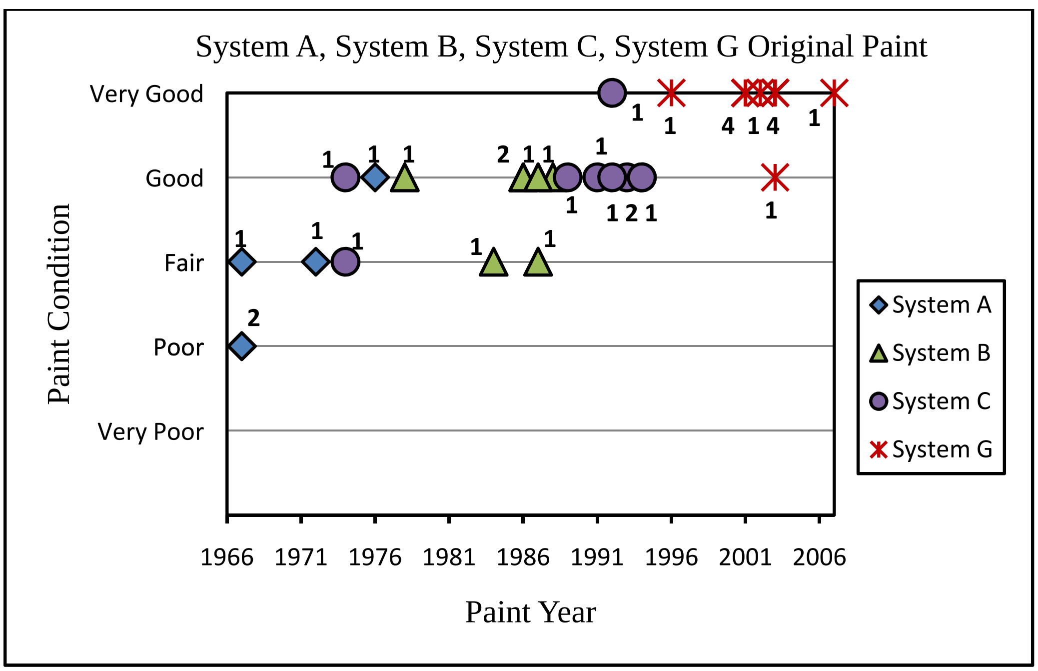


Figure 4.8 Condition Evaluation of Original Coating Systems.

Figure 4.9 summarizes the overall evaluation from all of the bridge observed during the course of the research, according to the current condition evaluation of the coating system. This overall data shows what could be expected, the older coating systems are typically in worse condition, the newer systems in better condition, generally. Of note in the figure is that the system S overcoating have a number of cases where their condition is poor or very poor. The system A, B, and C, which are typically much older, have many cases where their condition is above expectations given their age, these systems are in fair or good condition even after many years of service. In virtually every case, the performance of the coating systems results directly from the drainage conditions at the bridge. For system S coatings that have performed poorly, the existing coating system that was overcoated was in poor condition and the drainage continues to effect the overcoating. For system A, B and C systems that are performing well, the surface of the steel has been kept dry by proper deck drainage and/or deck rehabilitations. One assumes that a number of A, B and C coating systems have failed previously and have been recoated or overcoated, as previously discussed.

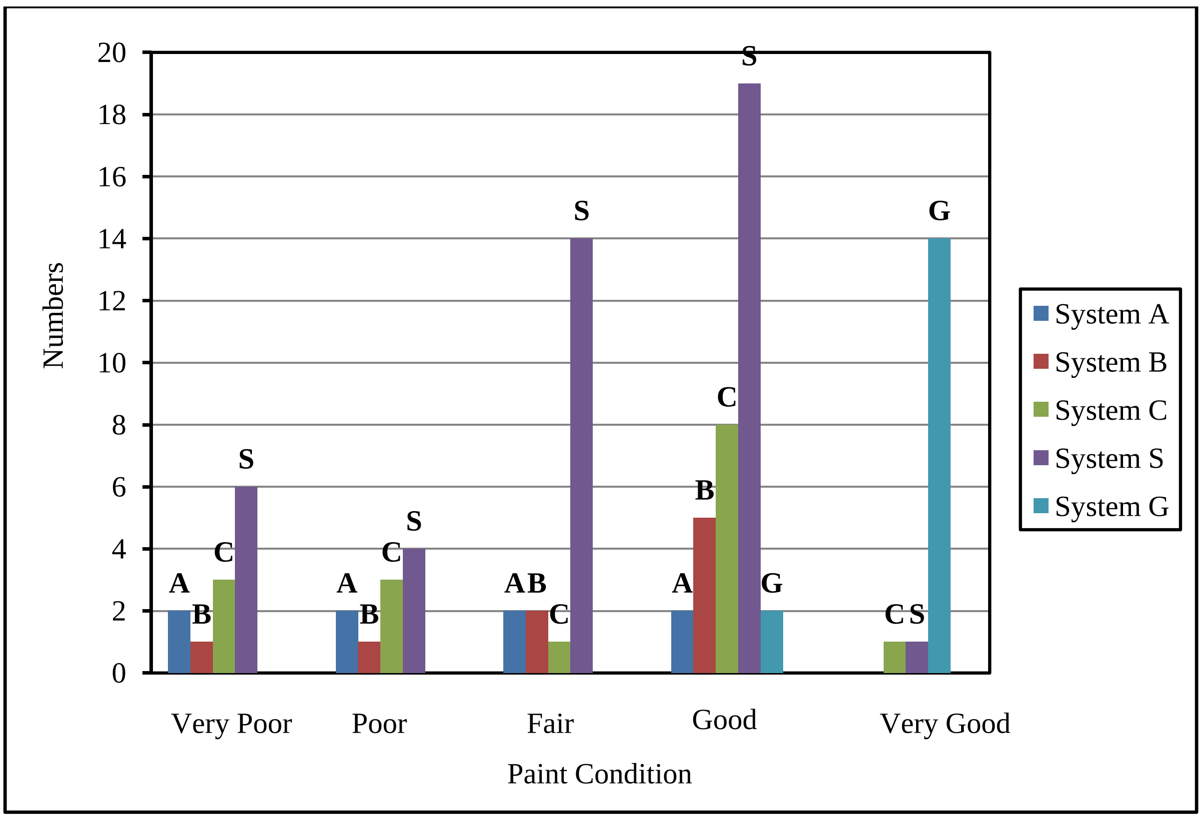


Figure 4.9 Overall Summary of Coatings Conditions Observed in the Study.

4.4 Service Environment

An effort was made to associate the condition of the coating with the service environment surrounding the bridge on which the coating was applied. Coating service environment is typically described in ranges from mild to severe, based on the amount of aggressive chemical and moisture in the surrounding environment. Although some variation exists among different standards, the five category general service environment rating system described in the task force report of December 2008 recommends these categories:

1) Mild- rural or residential with no industrial fumes or fall out.
2) Moderate- industrial plants present but no heavy contamination from industrial fumes or fall out.
3) Harsh- heavy industrial and chemical plant area with high levels of fumes and fall out.
4) Sweating Surface- assumed to be subjected to condensation during times of coating application.
5) Water Immersion or Splash- surface completely covered by water during normal operating conditions or conditions occurring during the winter after a snow event and the application of deicing materials.

Based on our survey, the number of bridges where airborne pollutants in a quantity high enough to significantly effect coating deterioration (categories 2 and 3) appear to be a relatively small percentage of the bridge inventory and can be treated as exceptions; the vast majority of bridges in Missouri are in mild/rural environments. These descriptions of the macro-environment, that is, the ambient environment surrounding the bridges, may have an effect on selected coatings performance in extremely aggressive environments, but in general the micro-environment, that is the localized drainage conditions at the bridge have such an overriding dominance on the coating performance, that more subtle distinctions of the surrounding macro-environment seem much less important. Additionally, contemporary controls on industrial emissions generally have greatly reduced the potential for industrial environments to be sufficiently harsh to show substantial effects on bridge coatings.

We found a limited number of low clearance rural bridges over waterways where there was evidence of sweating (category 4) and the sweat streaking appeared to have occurred after coating application. In addition to moisture from sweating, there was some evidence of coating deterioration resulting from moisture retained on coated steel surfaces from condensation, often forming around small bits of debris lying on horizontal girder flange surfaces. This occurs most frequently in the confined spaces at the end spans of low-clearance bridges over waterways. These bridges had not been painted with system G at the end-spans. The higher cost of system G when balanced against the low risk and low usage of the bridge make this a good decision, however greater attention to surface preparation and coating application of system S in these areas would improve longevity of the coating. However, correction of the exposure to wet-dry cycles is needed to experience full service life of the coatings, regardless of the repair strategy employed.

Category 5 (water immersion) appeared to have occurred irregularly on some rural bridges when the water level rose high enough to cover part of the substructure, but this did not appear to cause significant coating deterioration.

By far the greatest number of bridges surveyed that exhibited coating failures due to environmental factors were those where rain and deicing chemicals intermittently runs directly onto painted steel surfaces due to holes in the deck, leaking expansion joints, or runoff through guardrail slots. This has been discussed previously in the report.

5. CONCLUSIONS

This research included a literature search related to the current state of the practice for bridge coatings focused on over-coating and current methods for condition assessment. Guidelines for evaluating coating conditions in the field were developed. A field survey was conducted to assess the current conditions of the various coating systems in the Missouri bridge inventory including original coatings, recoating and over-coatings.

A comprehensive guide to condition assessment of coatings according to a subjective rating scale has been developed. This rating scale is not drastically different than the current rating system in Missouri. However, the different condition states have been defined somewhat differently in an effort to make it more likely that consistent evaluations will occur between different inspectors. Given the variability of the current ratings in the TMS data, applying this new condition assessment scheme can be expected to greatly improve the quality of the data available.

The guidelines establish condition states directly related to potential actions for maintenance of the coatings. Once these condition states are incorporated, for both mid-spans and beam ends, appropriate maintenance painting requirements can be more readily identified simply using a spreadsheet program. For example, under the developed rating scheme, bridges rated as Fair are candidates for limited over-coating/spot painting, bridge coatings rated as Poor are candidates for over-coating, and bridge coatings rated Very Poor require recoating. Maintenance painting activities as a preventative maintenance activity should focus on coatings rated as Fair and Poor. Field performance of overcoatings for a bridge rated as very poor is unlikely to be successful in extending the life of the coating substantially.

Visual guidelines for determining the appropriate ratings (condition states) for coatings have been developed. This visual guide is comprised of a set of exemplar photographs of bridge components in each of the 5 ratings utilized, and a field pocket guide for use as a reference by bridge inspectors. This is the most complete visual guidance for bridge condition assessment available currently. These guidelines will be of interest to other state DOTs interested in improving their coating condition assessment programs.

This survey noted a number of discrepancies between condition ratings in TMS and ratings done by the field team. Although ratings are subjective, too much subjectivity in TMS data quickly reduces its utility as a decision making tool. A simpler set of categories and field personnel thoroughly familiar with these categories would reduce subjectivity and improve the utility of the database. Reducing the rating categories from six to five, using a visual guide (appendix A) as a training tool, and providing a pocket guide (appendix B) to field inspectors will improve data quality immensely moving forward. For the bridges surveyed during the course of the project, it was found that the existing TMS data indicated that the coating was in better condition than it actually was when observed in the field for 39% of the bridges surveyed. The TMS data indicated a worse condition than what was found in the field 14% of the time, and was essentially consistent with the field evaluation for 47% of the bridges surveyed. Improving the data available in the TMS database will significantly improve the ability of MoDOT to get an overview of coating needs throughout the existing bridge inventory. Utilizing the guidance provided through the research should greatly improve the reliability of the condition assessments, i.e., the consistency of the evaluations, such that the database can be a useful tool in the future. Given that bridges are inspected on a 24 month cycle at most in Missouri, the time required to collect this data is not that significant.

In terms of the performance of coating systems currently utilized in Missouri, the following conclusions were made:

- Maintenance over-coatings with system S is often effective in extending the service life of coatings. Many over-coating efforts are in fair to good condition with up to ten years of service. The estimate of 10 to 15 years of service life for a well-applied system S coating was supported by the observations in the field. However, when overcoating at locations where corrosion was very significant and drainage patterns (i.e. leaking joints) are unchanged, early system S failures were observed. This is due to the combination of existing rusting not being fully removed by the surface preparation, chlorides remaining on the surface, and the continued exposure to wet-dry cycles.
- For coatings overall, the drainage of water from the deck onto the superstructure was the primary factor leading to service failure of the coating. Deterioration of the bridge deck to a poor condition is directly related to the failure of the coating system, regardless of the coating system. For system G, the situation of poor drainage characteristics was not observed, because these coatings are applied to modern structures where the drainage systems have modern designs that prevent drainage onto the superstructure.
- The system G coating system was performing well in all situations observed.
- System A, B and C with 35 to 40 years of service life were still performing well on bridges with effective drainage that kept the superstructure dry.

Most severe coating deterioration situations resulted from rainwater and deicing chemicals running directly onto structural members. This water comes from: holes and cracks in the deck, deck saturation, leaking expansion joints, and deck drains. Common sense tells us to plug the holes first, then repaint the steel and MoDOT is doing this as bridge renovations occur. Decks in poor condition, where saturation occurs in the deck due to corrosion induced damage, results in rapid deterioration of the coating systems on the primary members. Often, this initiates as corrosion on the top flange of the primary members, and this deterioration can be severe. Increased use of crack-sealing deck sealants may help reduce the rate of this type of deterioration; redecking operations coupled with recoating or overcoating where appropriate will also correct this and provide an environment where the new coating should perform well. In future designs, expansion joints over end-span bearings should be avoided, i.e. jointless bridges should be used where possible to preserve the coatings.

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PART II REPORT

TASK 2:

EVALUATION OF ADVANCED COATING SYSTEMS

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1. INTRODUCTION

Steel bridges are corroded inevitably due to the chemical reaction between the metal or metal alloy and the environment. Especially nowadays, these corrosion processes are even faster with the usage of the chloride salt deicing agent during the winter. According to research carried out by the Federal Highway Administration (FHWA), steel has the highest percentage of structurally deficient structures among the construction materials of highway bridges. Steel corrosion and deterioration have been mitigated by using proper coatings for decades. Before the United States (US) Environmental Protection Agency (EPA) regulated the usage of heavy metal and limited the amount of volatile organic compounds in the coating formulations, lead, chromium and other heavy metals-based coatings were effective, but are no longer used because of health and environmental issues. This had a far-reaching impact on the application of architectural and industrial maintenance coatings. The low solid coatings with high percentage of non-exempt solvent became obsolete with an emphasis on more and more environmental-friendly emissions. High solid, cross-link polymeric coatings featuring higher adhesion and tougher abrasion and chemical resistance were increasingly popular as a topcoat among the DOTs in the USA.

Table 1.1 MoDOT Structural Coating Systems in TMS.

System Type	Definition	No. Of Bridges
A system	Red lead/Brown lead/Aluminum	1041
B system	Red basic lead silico-chromate Brown basic lead silico-chromate Aluminum or Green basic lead silico-chromate	520
C system	Two-component inorganic zinc silicate primer Aluminum or Green vinyl finish coat	299
D system	Waterborne inorganic zinc silicate primer Aluminum or Green vinyl finish coat (field application)	5
E system	Waterborne inorganic zinc silicate primer (two coat system for shop application w/ no overcoat)	6
F system	High solids inorganic zinc silicate primer, green or gray tint (no top coat)	26
G system	High solids inorganic zinc silicate primer green or gray tint Epoxy intermediate High-gloss polyurethane finish coat, green or gray	177
H system	Three-component high solids inorganic zinc silicate primer Acrylic intermediate coat Acrylic finish coat, green or gray	30
S system	Calcuim sulfonate (penetrating sealer, primer, topcoat)	26

The coating systems used by the Missouri Department of Transportation (MoDOT) reflect the development of steel bridge coatings. The research undertaken in Task 1 of this project shows that there are 4561 bridge records in the TMS database. Table 1.1 shows the original paint systems of 2180 bridges cited in the TMS database.

Systems G, H and S are current candidate coating systems used for bridge maintenance. System G and system H can be applied on both new and existing bridges after removing the old paint. System S is used for overcoating an old intact and adherent paint, primarily the old lead based paint. MoDOT's structural steel coating program falls into three categories showed in Table 1.2.

Table 1.2 MoDOT Structural Coating Programs.

Program	Description
Internal coating program	Limited hand tool or power tool cleaning Coating system S
Contract Maintenance program	Commercial complete removal and blast cleaning to bare steel in field Coating system S, G or H
New Construction Program	Shop priming with field operation or total shop application Coating system G and H

MoDOT continues to evaluate new technologies and readily inserts new and improved coating systems into MoDOT's coating program. When an existing coating system is found good and intact condition wise, overcoating the old existing paint serves as the primary maintenance method to avoid the high cost of full removal of the old paint.

Task 2 of this project concentrated on the following areas. The first area was to introduce new coatings technologies including new materials, new formulations and new application methods which involve high-build, plural component systems such as polyurea. The second area was to evaluate the promising coating systems and compare them with current MoDOT system G and S through several standard laboratory and field tests. In addition, a field implementation and demonstration study of one or two new technologies can then be carried out at the completion of the first two activities.

2. OBJECTIVE

The focus of this task is to develop an improved, cost effective structural steel coating practice. The study considers a broad range of available coating types and results in recommendations that will provide low cost, low risk of failure systems for the most common scenarios. A comprehensive review of new coatings technologies included a review of test results and systems available through the American Association of State Highway and Transportation Officials (AASHTO) / National Transportation Product Evaluation Program (NTPEP) as well as other industrial resources. The data collected through this means as well as Task 1 on the performance of coatings in Missouri, the experience of other states with new coatings technologies were utilized to identify coating systems for further evaluation in Task 2 of this study. Any coatings that are found that have shown promise in other industrial applications that have not been fully exercised for Highway Bridge applications was also identified as candidates for evaluation and demonstration purposes. This includes high-build, plural component systems such as polyurea. Working closely with MoDOT partners, a test and evaluation plan was developed to effectively evaluate the potential for new or improved structural steel coatings. Upon development of the test plan, laboratory studies investigated mil thickness and surface conditions (in the case of overcoat applications) for improved bond and extended service life in the field. Additionally, this program provides recommendations for a supplemental field demonstration case study of one or more coating technologies in a field application as identified by MoDOT. The demonstration study provides an opportunity to observe the installation and initial performance of a new coating system(s) as well as the potential cost impacts and benefits of this new technology.

3. PRESENT CONDITION

The issue of painting or repainting steel bridges has received more and more attention. This is partly because of the strict regulations made by federal and state environmental agencies. Due to the demand of EPA regulations and awareness of environmental protection, there are all kinds of new types of coating systems invented and utilized for painting new bridges. Lead-based paints and high VOC paints are no longer allowed to be applied to bridges. Containment of debris and worker respiration protection is required when old paints with heavy metals are removed. These requirements increase the cost of repainting a bridge.

3.1 Present Condition on Coating Systems for New Steel Bridges

Unlike repainting or overcoating an old bridge, the only consideration of painting a new bridge is to select a proper high performance coating system. Most state DOTs utilize approved two-coat systems or three-coat systems for structural steel paint. MoDOTs current coating systems are system G and system H (see Table 1.1). Other possible choices by other state DOTs are zinc / epoxy / siloxane, zinc / polyaspartic, zinc / moisture cure urethane and zinc / epoxy / fluoropolymer. The coating systems with organic zinc or inorganic zinc primer are very popular in the United States. According to research from the KTA-TATOR, Inc. (Helsel, 2006), the zinc primer is able to last as long as the service life of the steel bridge if the maintenance job of intermediate and topcoat is done timely and effectively.

The need to develop a system that is relatively low cost, with easy installation, and does not require frequent re-application is still in high demand. Within the past few year’s technologies in polymer based systems to repair and strengthen structural elements has advanced, but little has evolved to address or investigate corrosion of steel elements other than epoxy coated or urethane based coating systems to mitigate the corrosion problem. During the past decades, polyurea coatings have become increasingly popular. The chemistry and properties of the polyurea vary a lot compared to that of polyurethane. In addition, a new type of polyurea, polyaspartic polyurea which is a promising coating system for steel structures, has been developed since the early 2000’s. The advantages of polyurea coatings are low volatile organic content (VOC) or no VOC combined with a relatively short pot life which facilitates the application process. Several polyurea coating systems were evaluated in this study.

3.2 Present Condition on Coating Systems for Existing Steel Bridges

In addition to the EPA regulations, the challenge of repairing or replacing old bridge paint is the issue of dealing with the old lead-based paint: Lead-based paint has been used in bridge coatings for more than 100 years. Based on a report by the National Cooperative Highway Research Program in 1998 (Neal, 1998), there are more than 200,000 steel bridges in service throughout the nation. Approximately 80 to 90 percent of the steel bridges are coated with lead or other toxic heavy metal-based coatings. The potential regulation issues are causing owners to rethink corrosion protection strategies. The strategies include (1) doing nothing to the coating and eventually replacing the steel, (2) painting over the old coating (overcoating), or (3) total removal of the existing coatings. The great appeal behind overcoating the bridge is primarily cost reduction; there is no need to fully remove the lead-based system. For most overcoating projects, the requirements for containment are much less stringent, as less dusty surface preparation methods are normally used. In 1997, the Society for Protective Coatings (SSPC) conducted a survey which showed that the average national costs were \$7.75 and \$4.40 per ft^2 for full removal and overcoating.

3.2.1 Major Challenge of the Lead-based Paint on the Steel Structures

The paint system on these structures has a limited durability because of the deteriorating effects of aging of the paint, salts and moisture, ultraviolet radiation, and physical and mechanical abuse. Any activity to restore or maintain protection and appearance will result in some disturbance to the lead-based paint that could cause adverse effects. Coatings on many of the structures are in very poor condition with paint peeling, chipping, and eroding, and active corrosion of the metal occurring. If left unchecked, the corrosion can cause structural damage to the bridges within the next 5 to 15 years (O'Donoghue, Garrett, & Datta, 2002). In the meantime, the coatings still present a potential for environmental pollution. Leaving the coating undisturbed can also cause problems because the lead-based paint will eventually erode or flake off the bridges into the environment. The cost of removing or maintaining coatings on bridges is extremely high compared to historical spending on painting by highway agencies.

3.2.2 Desirable Properties for a Good Overcoat Primer

To achieve optimum functioning of the overcoat system, the properties of overcoating systems are summarized here (O'Donoghue et al., 2002):

- Wide compatibility with generically different coatings (especially alkyds)
- Good performance over hand, power tool and water-jetting surface

- Proven long-term success
- Significant penetration into voids and surface imperfections of the old coating
- Penetrant material has sufficiently high pH to neutralize acidity in pack rust
- High degree of wetting, adhesion, and capillary action
- High-volume solids and, preferably 100% solids
- Good barrier properties
- Zero or low shrinkage during cure
- Penetrant sealer remains wet for a prolonged period prior to cure
- Moisture-tolerant and able to displace or react with water
- Flexibility
- Low-temperature
- Optimal application and flow characteristic
- Minimal stress at the substrate coating interface
- Resistance to hydrothermal stress
- Capability of rust consolidation
- Low Dry film Thickness (DFT)
- Ultraviolet resistance
- Applicator and environmental friendliness

3.2.3 Survey by SSPC in 1993

According to the survey conducted to the coating and lining industry in 1993 by SSPC (Hower, 1993), four dominant mechanisms resulted in good overcoating performance:

- Tenacious adhesion,
- Good ability to wet and/or penetrate the surface,
- Benign influence on the existing coating, including compatibility and imparting minimal stress from solvent lifting, and
- Barrier properties for corrosion protection.

3.2.4 Commonly Used Overcoating Systems

The properties of several commonly used overcoating systems are illustrated in Table 3.1 below.

Table 3.1 Common Overcoating Systems.

Overcoat systems	Properties
Calcium sulfonate sealers, primer and topcoat	• Displace water, neutralize surface acidity, and give good adhesion when applied to a suitable substrate. • Never dry completely and remain active for years which is beneficial on joints and connections
Epoxy	• Excessive film thickness will exert strong contractive curing force. Crack and split of underlying coatings. • Low viscosity, favorable surface tensions and high alkalinity in good coatings.
Moisture-cured urethanes	• Isocyanate groups react with water vapor in the air to form tough polymers by releasing carbon dioxide. • Film build limit within 4 mils. One component for easy application; Good in high humidity. Low temperature cure.

4. TECHICAL APPROACH

Reliable accelerated laboratory tests are indispensable for evaluating the effectiveness of the coating systems and predicting the performance of the coating systems in the field. There are several standard specifications that can be consulted for testing coating systems for structural steel, which include AASHTO standards, ASTM standards, Federal standards and the Society for Protective Coating (SSPC) standards. In the 2004 "Missouri Standard Specification Book for Highway Construction", there are two sections addressing coating issues, Section 1045 and Section 1081. The lab and field test matrix of task 2 was developed according to the standards and specifications cited above.

4.1 Test Matrix

A two-phase test matrix was developed according to the requirements of the MoDOT specifications. There are numerous kinds of different tests which can define different characteristics of coating systems. The tests that were selected in the matrix are the ones to evaluate the durability and long-term performance which MoDOT and this research study primaily focuses on. Table 4.1 shows the intial prescreened coating systems on the structural coating market. In total, 11 coating systems from 5 paint maunfactures were selected within the test matrix for evaluation in phase I, Task 2 of the research program. In phase II of Task 2, two overcoating paints were choosen to compare with the current MoDOT CSA system.

4.2 Phase I Test: Coating Systems for New or Bare Steel

4.2.1 Test Specimen Preparation

The plates used in Phase I are A-36 hot rolled, 3/8-inch-thick structural steel plates. The plates were blast cleaned to near white condition with a 2.5-mil profile. The plates are KTA test plates made for labratory or field coating studies. The size of plates for all the labratory tests are 1/8-in. ×3-in.×6-in.

All the test plates except coating system A were prepared by respective paint manufacutures and the coatings were applied within the dry film thickness (DFT) range recommended by their manufacturers. System A specimens were coated on the Missouri University of Science and Technology (Missouri S&T) campus by physical facilities staff trained in professional paint application strictly following manufacturer's guidelines. All of the test plates were coated on both sides with complete coating systems. The edges were sealed and protected by either applying vinyl tape or painting epoxy. There were 12 coating systems selected including current MoDOT system G, which is a MoDOT approved coating system. Table 4.2 details the coating systems studied, their study identification code, the manufacturer id, and a brief coating system description. Following this, the various test methods and devices utilized in this research study are presented and described.

Table 4.1 Test Matrix for Task 2

PHASE I NEW COATING/ RECOATING SYSTEM- LAB TESTS

1. **Test panels: 1/8"×3"×6" A36 Hot rolled flat steel panel: blast cleaned, near white, 2.5 mils profile.**
2. **Coating system G specimens were selected and are prepared by MoDOT.**
3. **New coating system specimens are provided and prepared either by manufacturers or Missouri S&T staff according to manufactures' or research team recommendation.**
4. **The panel shall be clean by solvent to remove any flash rust and grease before coating applied (SSPC-SP1).**

Coating System	NO.	Coating System Description	Sub-Group NO.	Manufacturers	Primer Surface Tolerant/ Application	Test 1 Slip Coefficient	Test 2 Salt fog Resistance test	Test 3 Cyclic Weathering Resistance Test	Test 4 Abrasion Resistance Test	Test 5 Adhesion Test	Test 6 Freeze-Thaw Stability	Test 7 Coating Identification Tests	Test 8 Two-year Atmospheric Testing
G	1	Zinc+Epoxy+Ployurethane	1-A	N.A.	No, SSPC 6, 1-3 mils/ Spray		√	√		√	√		√
New	2	Zinc+Polysiloxane	2-A	Manuf H	No, SSPC-SP6 2mil profile/Brush or roll		√	√		√	√		√
			2-B	Manuf D			√	√		√	√		√
	3	Micaceous iron oxide based zinc primer + polyurea coating	3-A	Manuf H	Yes /Spray		√	√		√	√		√
			3-B	Manuf N	Yes /Spray		√	√		√	√		√
	4	Mio-zinc+Polyaspartic polyurea Polyaspartic)	4	Manuf A	Yes/ Brush or roll		√	√		√	√		√
	5	Polyaspartic Polyurea coating 7-a high solid epoxy + Polyaspartic 7-b 100% solid polyurea+ Polyaspartic	5-A	Manuf H	No, SSPC-SP6 2mil profile/Spray		√	√		√	√		√
			5-B	Manuf H			√	√		√	√		√
	6	High Solid Epoxy+Polyurea High Solid Epoxy+Polyurea coating	6-A E A200	Manuf H	No, SSPC-SP6 2mil profile /Spray		√	√		√	√		√
			6-B A 450SS	Manuf H			√	√		√	√		√
	7	Polyurea Designated primer+Polyurea (waterproof)	7	Manuf A	No, SSPC-SP6 2mil		√	√		√	√		√
	8	Urethane primer+polyurea topcoat	8	Manuf I	NA		√	√		√	√		√
PHASE II OVERCOATING SYSTEM- LAB TESTS **5. LBP plates were included from decommissioned structure with MoDOT assistance and approval.** **6. Recoating and encapsulation systems were chosen from phase I based upon test result performance/effectiveness.**													
CSA System (Control System)	R 1	Calcium Sulfonate Rust Penetrating + Calcium Sulfonate Primer + Calcium Sulfonate Topcoat	TBD	TBD									
Recoatable coating System from Phase I	R2-R#	The quantity will depend on the performance of new coating system in phase I	TBD	TBD									

Table 4.2 Coating System Summary in Phase I and Identification Code.

Manufacturers	Coating System in Phase I	Sub Group No.	Brief Coating System Description
G1		**1**	Zinc + Epoxy + Ployurethane
H	**H1**	**1**	Zinc + Polysiloxane
		2	High Solid Epoxy + Polyaspartic
		3	100% solid polyurea + Polyaspartic
		4	High Solid Epoxy + Polyurea A
A	**A1**	**1**	Miozinc+Polyaspartic polyurea
P	**P1**	**1**	Designated primer + Polyurea
N	**N1**	**1**	Zinc Urethane + Epoxy + Ployurethane
		2	Zinc Urethane + Epoxy + Fluoropolymer
I	**I1**	**1**	Urethane primer 1 + Aromatic polyurea +Urethane topcoat
		2	Urethane primer 2 + Aromatic polyurea + Urethane topcoat
		3	Polyamine epoxy + Aromatic polyurea + Urethane topcoat

4.2.2 Physical Property Measurement

4.2.2.1 Coating Thickness

The dry film paint thickness measurements in this study were taken in accordance with ASTM Method D1186-01 “Standard Test Methods for Nondestructive Measurement of Dry Film Thickness of Nonmagnetic Coatings Applied to a Ferrous Base” (ASTM, 2001) using an Elcometer 456 coating thickness gauge as illustrated in Figure 4.1.

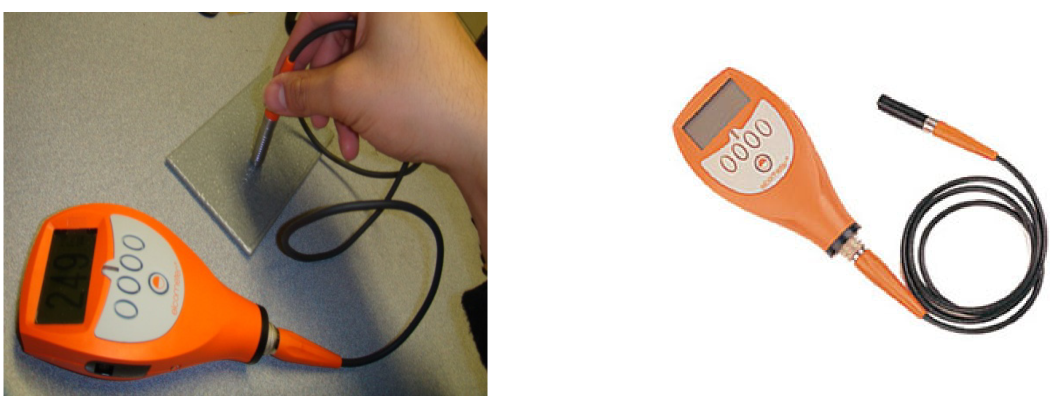


Figure 4.1 Elcometer 456 Coating Thickness Gauge.

4.2.2.2 Specular Gloss

The specular gloss measurements are performed in accordance with ASTM Method D523-08 “Standard Test Method for Specular Gloss” (ASTM, 2008) with a 60° geometry configuration as illustrated in Figure 4.2.

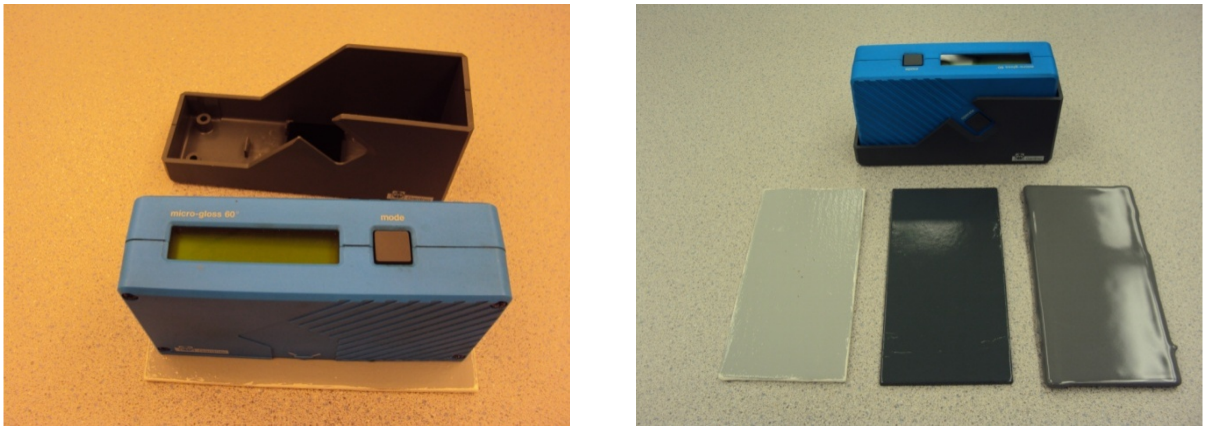


Figure 4.2 BYK-gardner Specular Gloss Equipment.

4.2.3 Salt Fog Test

Salt fog test evaluation was performed in accordance with ASTM Method B117-09 “Standard Practice for Operating Salt Spray (Fog) Apparatus” (ASTM, 2007). This test is a standardized test which is widely used to evaluate the corrosion resistance of the coated samples. The salt fog solution uses sodium chloride (5% NaCl solution by weight in the test). The specimens for this test were scribed before exposure with straight lines by a carbide tip cutting tool.

Figure 4.3 Salt Fog Test Setup.

The steel substrate was exposed along the entire length of the scribe. The scribing, a deliberate simulation of coating failure, is used to simulate the failure observed when coated products are subjected to abrasion or accidental damage and then exposed to corrosive influences. All the coating systems are supposed to be exposed for a duration of 3,000 hours. The blistering and rust creepage were evaluated at each 500 hour increment of exposure. Figure 4.3 illustrates the Salf fog chamber and representative cycled specimens within the chamber.

4.2.4 QUV Weathering Resistance Test

The QUV test simulates the weathering conditions which may occur outdoor throughout the year. The test combines the ultraviolet sunlight and moisture condensation as illustrated in Figure 4.4. Fluorescent UV lamps in the QUV equipment, having 295nm to 365nm wave length spectrum, produce the UV light which is responsible for most of the sunlight damage to polymer materials (topcoat) exposed outdoors. The condensation cycle process is done by water supply and water heater to form the dew on the surface which is responsible for most outdoor wetness.

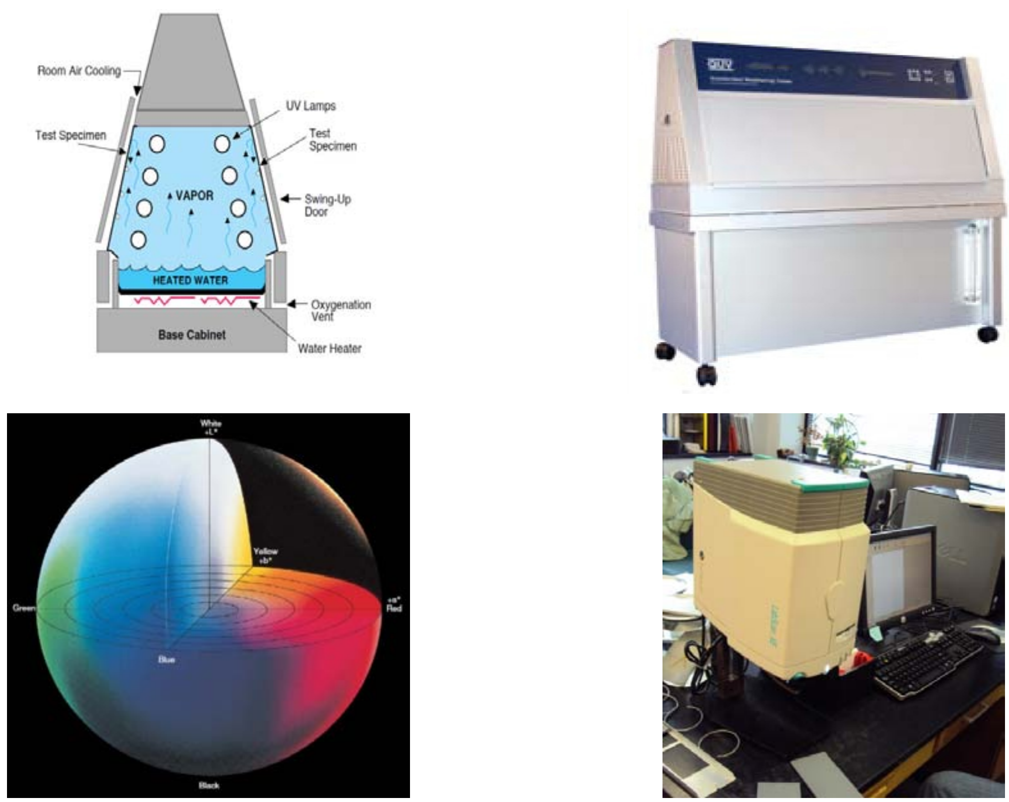


Figure 4.4 QUV Weathering Equipment and Color Coordination.

The test is recommended to run 4000 hours in total to evaluate the accelerated weathering resistance. The color of every topcoat was measured every 500 hours by spectrophotometer during the test. The difference (i.e. variation) was recorded in accordance with CIE 1976 L*a*b* color space using ASTM Method D2244-09 “Standard Practice for Calculation of Color Tolerances and Color Differences from Instrumentally Measured Color Coordinates” (ASTM, 2009). The color difference, ΔE^*, is used to determine the degree of color change.

4.2.5 Adhesion Test

ASTM Method D4541-09 “Pull-off Strength of Coatings Using Portable Adhesion Tester” is the standard for the adhesion test as illustrated in Figure 4.5. The adhesive used to perform this test is a 100 percent two component epoxy. At least two tests were performed on each panel as long as the failure modes and strength values were consistent. If results varied, a third test was undertaken.

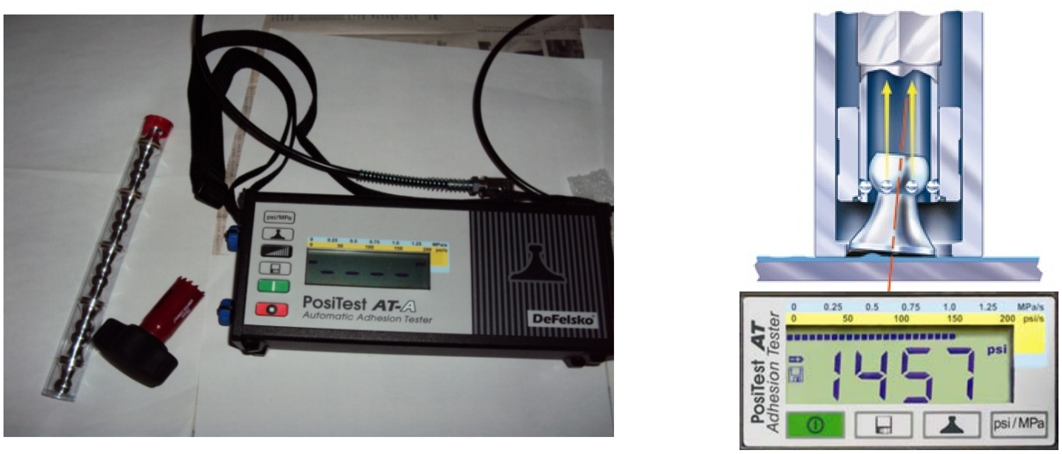


Figure 4.5 Adhesion Test Equipment.

There are several failure modes that may occur in an adhesion test as exhibited in Figure 4.6. These include:

- Adhesion Break: A break between coating layers or between the substrate and first coating layer,
- Cohesion Break: A break within a single coating layer,
- Glue Break: Coating adhesion and/or cohesion strength exceeds bonding strength of the adhesive, or
- A multiple-location break including breaks above.

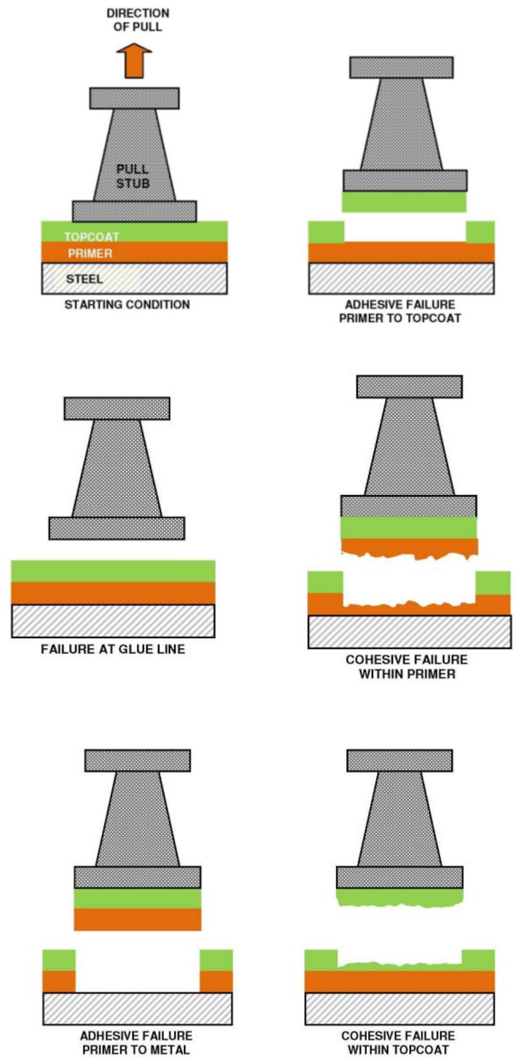


Figure 4.6 Adhesion Test Failure Modes.

4.2.6 Freeze-thaw Stability Test

The freeze-thaw stability test is referred to as Test No. 6 in the National Transportation Product Evaluation Program NTPEP coating evaluation tests. Prepared panels are exposed to a 30-day freeze/thaw/immersion cycle. One 24-hour cycle shall consist of 16 hours at –30°C ± 5º (-26.6ºC at freezer) followed by four hours of thawing at 50°C ± 5ºC (50ºC at oven) and four hours tap water immersion at 25°C ± 2ºC (water bath by submersible heater). Figure 4.7 illustrates the equipment used at Missouri S&T to undertake the freeze-thaw stability tests.

Figure 4.7 Freeze thaw Stability Test.

4.2.7 Electrochemical Test

4.2.7.1 Electrochemical Impedance Spectroscopy (EIS)

Electrochemical impedance spectroscopy (EIS) has been used in the study of corrosion for decades. The spectroscopy obtained in the test can be used to evaluate and examine the steel rebars in concrete, underground pipelines, coated metals, etc. During the impedance measurements, a small amplitude signal, voltage between 5 to 50 mV is applied to a specimen over a range of frequencies from 0.001 to 100,000Hz.

Impedance, Z (ω) is expressed into real part Z' (ω) and imaginary part Z" (ω). The results from the EIS test consists of a Nyquist plot of Z' (ω) as a function of Z" (ω) and bode plot of log|Z| and log θ versus frequency in herz. Figure 4.8 illustrates the EIS test set used for this study at the Materials Research Center at Missouri S&T.

To predict the performance of coating systems, EIS measurements were performed on samples with an exposed circular area of 1 cm^2 and an artificial 1/8" diameter drill pit (a flat exposed area made by an endmill).

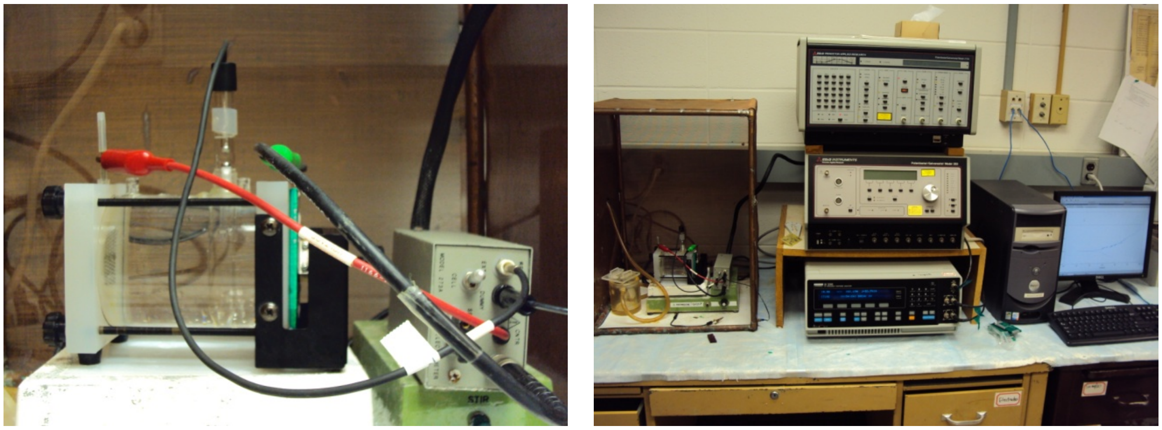


Figure 4.8 Electrochemical Test Setup.

4.2.7.2 Potentiodynamic Polarization

The potentiodynamic polarization is a corrosion measurement test which can provide information on corrosion rate, corrosion potential, critical current density, passivation potential, etc.

4.2.8 Post Corrosion Interface Analysis

After 3000 hours of salt fog exposure, the vast majority of the test panels did not display any signs of blistering appearance. The dry film thickness (DFT) of the coatings were much higher than conventional bridge coating systems (more than 90 mils in DFT). Therefore, it was difficult to evauate the cutback and creepage of the coating system using normal methods as the coating was thick and had good adhesion to the substrate. The undercut and creepage were viewed under the microscope by encapsulating the scribe part with epoxy as illustrated in Figure 4.9.

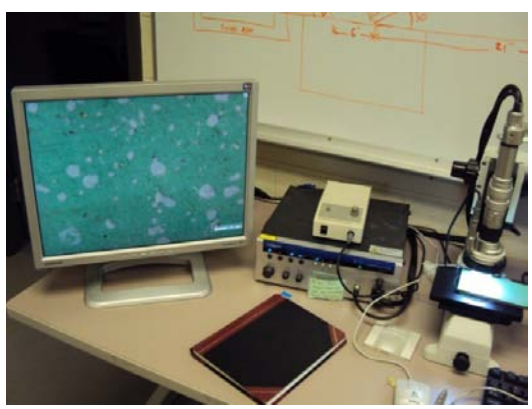


Figure 4.9 HiRox-digital Imaging System Setup.

4.2.9 Atmospheric Exposure Testing

Adapted from NTPEP Test No. 8, panels were inclined at an angle of 30 degrees from level along the long leg as illustrated in Figure 4.10. The panels are in the process of being exposed for two years and then will be photographed, inspected, and analyzed. The rack is located in a rooftop Greenhouse in Butler Carlton Civil Engineering Hall on the Missouri S&T campus. In this environment, the temperature is maintained at >65°F year round, with a relative humidity maintained at 100% with direct ultraviolet (UV) exposure to acclerate the exposure conditioning. The panels are sprayed with a high level chloride solutions in addition. The results of this atmosphereic exposure test will be submitted to MoDOT as a separate addendum report when the two year studies have been completed.

Figure 4.10 Atmospheric Exposure Testing Setup.

4.3 Phase II test: Overcoating Systems for Existing Structures

4.3.1 Test Specimen Preparation

4.3.1.1 Steel Structural Components with the Old Lead-based Paint

In order to study the overcoating system long-term performance and durability, the panels in phase II were cut from a decommissioned steel bridge component using water jet technology. This was undertaken such that the existing coating system would not be damaged. Other techniques, such as flame cutting or mechanical cutting using blades, result in coating damage. The steel components provided by MoDOT have two different coating systems. Figure 4.11 (top left and right images) illustrates the I-section beam with MoDOT coating system B. Figure 4.11 (bottom left and right images) illustrates the C-section diaphragm with MoDOT coating system C.

Figure 4.11 Old Decommissioned Bridge Components.

4.3.1.2 Surface Preparation for Overcoating Systems

The cleaning process for these samples was undertaken using the following steps. These steps were undertaken to simulate the MoDOT internal coating program which utilizes very limited hand tool or power tool cleaning for overcoating the old paint.

- Solvent clean per SSPC-SP1: Remove all visible oil, grease, soil, drawing and cutting compounds and other soluble contaminants from the surface. Wipe or scrub the surface with rags or brushes wetted with solvent. Use clean solvent and clean rags or brushes for the final wiping.
- Mechanical cleaning per SSPC- SP2: Cleaning all the areas of rusted steel, loose, cracked or brittle paint until tightly adhered paint is obtained without rust or blisters.
- Hand tool wash with commercial cleaning agent: Remove loose paint, dirt and other deleterious materials.

4.3.2 Coating Systems

Three overcoating paint systems were investigated and applied to 1/8-in.×3-in.×6-in. steel plates cut from the old bridge components as described in Section 4.3.1.1. The coating surface investigation was carried out by using the HiRox-digital imaging system at Missouri S&T. Table 4.3 summarizes the coating systems studied, their study identification code, the manufacturer id, and a brief coating system description.

Table 4.3 Coating System Summary in Phase II and Identification Code.

Manufacturers	Coating System In phase II	Sub Group No.	Brief Coating System Description
CSA		**1**	Calcium sulfonate sealer, primer, topcoat
A	**A2**	**1**	Polyaspartic polyurea topcoat
E	**E2**	**1**	Rust inhibitive primer + intermediate coat+waterborne acrylic topcoat

4.3.3 Salt Fog Test

Section 4.2.3 describes the details of the salt fog test also utilized in this phase of the study. Under Phase II, three overcoating systems were evaluated on two types of old lead-based paint systems.

4.3.4 Adhesion Test

As described in Section 4.2.5, the adhesion test is an important test to show how well the paint is adhered to the substrate. When it comes to overcoating old paint systems, this method is used to help determine the maintenance strategy.

4.3.5 Freeze-thaw Stability Test

The cyclic freeze-thaw stability test was undertaken as the description in Section 4.2.6. In combination with the adhesion test, studies were carried out to show how the overcoating system is compatible with the old existing paint system.

4.3.6 Electrochemical Test

As described in section 4.2.7, the electrochemical impedance spectroscopy (EIS) was also applied to the specimens of Phase II. Using the results obtianed from the EIS test, a general decision can be made whether the overcoating systems are good at protecting the old structural steel.

5. RESULTS AND DISCUSSION (Evaluation):

5.1 Physical Measurement

5.1.1 DFT Measurement

Table 5.1 shows the coating thickness on the plates as measured when received using the Elcometer 456 DFT gauge. Recommended DFTs, also presented in Table 5.1, were obtained from the technical data sheets from the respective manufacturers. System G was prepared by MoDOT personnel at the Jefferson City, MO Chemical Lab. Coating systems H, N and I were prepared by their respective manufacturers using the bare steel plates in the same condition. System A was prepared by Physical Facilities Group at Missouri S&T.

Table 5.1 Thickness Measurement Results.

Manufacturers	Coating System Code	Sub Group No.	Max.	Min.	Average	Recommended DFT
System G		01	19.2	12.5	15.7	8-15
H	H1	01	9.4	3.59	6.31	5-11
		02	12.1	7.8	9.9	9-13.5
		03	85	45.3	62.6	48-72
		04	77	44.5	62.6	61-81.5
A	A1	01	30.8	16.7	25.02	9-15
P	P1	01	42.1	14.2	24.25	14-60
N	N1	01	15.9	8.7	12.51	7.5-18.5
		02	14.4	9.6	12.33	7.5-11.5
I	I1	01	101	60	81.2	42
		02	65	35.9	50.2	42
		03	86	32.4	51	42

Table 5.2 summarizes the application methods which also reflect the accuracy of thickness application. Spray (conventional air spray application and airless spray application) is the most appropriate method which has both accuracy and efficiency. The plural component spray head system is used for two component paint having a short pot life at ambient temperatures, like polyurea. The roller application (System A) gives a less desirable outcome for small area application.

Table 5.2 Application Methods Summary.

System code	Sub. System No.	Primer / intermediate coat / topcoat
System G	01	Air spray / Air spray / Air spray
H1	01	Air spray (or Airless) / Air spray (or Airless)
	02	Airless spray / Plural component heated spray
	03	Plural component heated spray / Plural component heated spray
	04	Airless spray / Plural component heated spray
A1	01	Airless spray (or Air spray, Brush, Roller) / Roller (or Airless spray, Air spray, Brush)
P1	01	Roller / Plural component spray system
N1	01	Air spray (or Airless) / Air spray(or Airless) / Air spray (or Airless)
	02	Air spray (or Airless) / Air spray(or Airless) / Air spray
I1	01	Air spray / Plural component spray head system
	02	Air spray / Plural component spray head system
	03	Air spray / Plural component spray head system

Table 5.3 Sag Resistance of Each System.

System code	Primer (mils)	Intermediate coat (mils)	Topcoat (mils)
G	N.A.	8 (min.)	8 (min.)
H1-01	8	[redacted]	20
H1-02	12	[redacted]	8
H1-03	No pot life	[redacted]	8
H1-04	12	[redacted]	No pot life
A1-01	18	[redacted]	25-30
P1-01	9	[redacted]	No pot life
N1-01	8	60	12-14
N1-02	8	60	5
I1-01	N.A[1]	No pot life	N.A
I1-02	N.A	No pot life	N.A
I1-03	N.A	No pot life	N.A

[1] The information was not available at printing.

Table 5.3 and Table 5.4 detail the sag resistance and Volatile Organic Compounds (VOC) Content respectively according to the information provided by the manufacturers. Polyurea based coating systems have no sag and zero VOC due to the rapid reaction of two-part materials. There is no solvent evaporation during the cure of polyurea. Therefore, the pot life is zero for polyurea products.

Table 5.4 VOC for Each Coating (Unreduced).

System code	Primer	Intermediate coat	Topcoat
System G (based on two qualified products)	2.40-3.00 lb/gal	1.60-1.72 lb/gal	2.40-2.72 lb/gal
H1-01	2.67 lb/gal	[redacted]	2.00 lb/gal
H1-02	2.00 lb/gal	[redacted]	0.00 lb/gal
H1-03	0.00 lb/gal	[redacted]	0.00 lb/gal
H1-04	2.00 lb/gal	[redacted]	0.00 lb/gal
A1-01	0.80 lb/gal	[redacted]	1.70 lb/gal
P1-01	0.00 lb/gal	[redacted]	0.00 lb/gal
N1-01	2.68 lb/gal	2.40 lb/gal	0.77 lb/gal
N1-02	2.68 lb/gal	2.40 lb/gal	2.93 lb/gal
I1-01	0.83 lb/gal	0.00 lb/gal	2.80 lb/gal
I1-02	0.00 lb/gal	0.00 lb/gal	2.80 lb/gal
I1-03	N.A.	0.00 lb/gal	2.80 lb/gal

5.1.2 Gloss Measurement

The gloss of the plates used for the QUV weathering test in Phase I were measured using a digital gloss meter both before the QUV weathering test and after 4000 hours QUV of the weathering test. Table 5.5 shows the measurement results.

Table 5.5 Gloss Measurement Results.

Specimen Code	Unexposed Part	Exposed Part	Average of the Systems
G1-01	34.6±0.8	2.5±0.4	37.5
G1-02	43.7±0.8	2.2±0.1	
A1-01	38.6±2.6	29.8±2.0	42.1
A1-02	69.5±3.6	54.1±1.8	
P1-01	8±1.2	1.6±0.1	17.7
P1-02	16.6±4.8	1.5±0.1	
H1-01	54.4±3	29±0.8	71.9
H1-02	57.8±3.2	46±2.8	
H2-01	85.3±1.8	79.7±0.8	85.8
H2-02	85.6±0.6	79.0±0.8	
H3-01	82.7±1.6	75.6±0.8	86.1
H3-02	82±3.2	72.8±4.2	
H4-01	78.2±1.8	1.3±0.2	83.2
H4-02	77.4±1.6	1.1±0.2	
N1-01	57.1±2.4	46.8±2.8	58.1
N1-02	59.2±0.8	41.9±0.6	
N2-01	76±3.6	76±0.8	77.5
N2-02	79.1±1.2	77.4±0.4	
I1-01	N.A.[2]	N.A.	N.A.
I1-02	N.A.	N.A.	
I2-01	N.A.	N.A.	N.A.
I2-02	N.A.	N.A.	
I3-01	N.A.	N.A.	N.A.
I3-02	N.A.	N.A.	

5.2 Salt Fog Test Results

All the results were documented by photos at every 500 hour intervals in Appendix C. Three plates for each system were placed in the salt fog cabinet. Table 5.6 shows the results which describe the blistering and rust accumulation near the scribe by observation after 3000 hour exposure.

[2] The information was not available at printing.

Table 5.6 Salt Fog Test Results after 3000-hr Exposure.

System			Technical Sheet Document	Test results
G1			N.A.	• No blistering developed on surface • Largest rust accumulated 1.75 mm • Bleeding occurred slightly
H	**H1**	1	Primer: ASTM B117, 7000 hrs Rating: 9 per ASTM D610 rusting Rating: 9 per ASTM D714 blistering	• No blistering developed on surface • Largest rust accumulated 2.5 mm • Bleeding occurred
		2	Primer: ASTM B117, 1000 hrs Rating: 10 per ASTM D610 rusting Rating: 10 per ASTM D714 blistering	• No blistering developed on surface • Largest rust accumulated 5 mm • Bleeding occurred heavily
		3	Primer: ASTM B117, 3000 hrs Blisters, no corrosion from scribe 5.0 mm	• No blistering developed on surface • Largest rust accumulated 3.5 mm • Bleeding occurred
		4	Primer: ASTM B117, 1000 hrs Rating: 10 per ASTM D610 rusting Rating: 10 per ASTM D714 blistering	• No blistering developed on surface • Largest rust accumulated 3 mm • Bleeding occurred
A	**A1**	1	ASTM B117, 3000 hrs Full system with 3-mil primer Rating: 10 per ASTM D1654 scribe Rating: 10 per ASTM D714 blistering	• No blistering developed on surface • Largest rust accumulated 2 mm • Bleeding occurred slightly
P	**P1**	1	N.A.	• No blistering developed on surface • Largest rust accumulated7 mm • Bleeding occurred heavily
N	**N1**	1	N.A.	• No blistering developed on surface • Largest rust accumulated 2 mm • Bleeding occurred slightly
		2	N.A.	• No blistering developed on surface • Largest rust accumulated 2.5 mm • Bleeding occurred slightly
I	**I1**	1	N.A.	• No blistering developed on surface • Largest rust accumulated 2.5 mm • Bleeding occurred
		2	N.A.	• No blistering developed on surface • Largest rust accumulated 2.5 mm • Bleeding occurred slightly
		3	NA	• Blistering developed on surface of one plate • Largest rust accumulated 4 mm • Bleeding occurred heavily

According to the evaluations and descriptions presented in Table 5.6, system G, having high solid inorganic zinc silicate as its primer, performed the best of all the systems in phase I. Systems A1-01, N1-01, and N1-02 performed well as expected due to the existence of organic primer. System A1-01, which used a ployaspartic polyurea as the topcoat, and system N2-02, which used a fluoropolymer topcoat, had remarkable performance in the lab tests. Both of these systems had better (i.e. higher) adhesion strength and higher UV weathering stability than other coatings with zinc primer. Besides system A1-01, systems H1-03, H1-04, and I1-02 also performed very well as far as polyurea type coatings systems were concerned in the salt fog testing evaluation. Some ployurea type coatings investigated had less desirable test results due to the inferior performance of their primers. The primers were vulnerable to the salt fog test which can be seen in Figure 5.1.

G1-01 primer-2000hrs

A1-01 primer-2000hrs

N1-01(02) primer-2000hrs

H1-02(04) primer-1500hrs

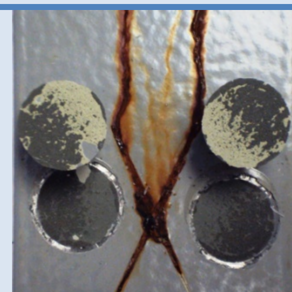
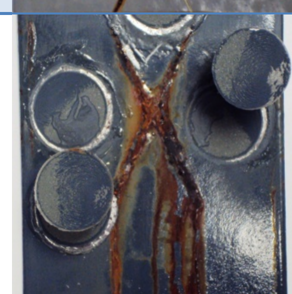
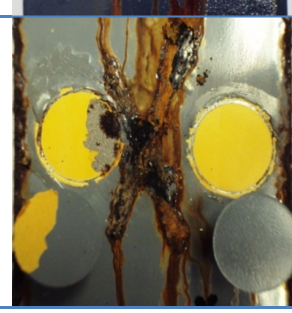
H1-03 primer-1500hrs

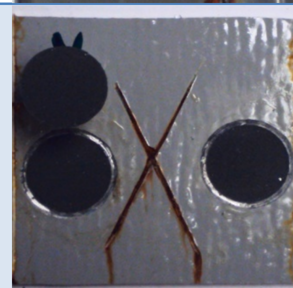
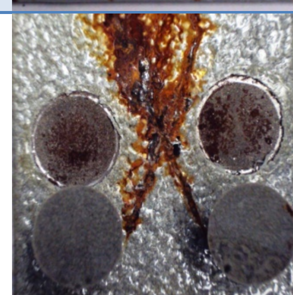
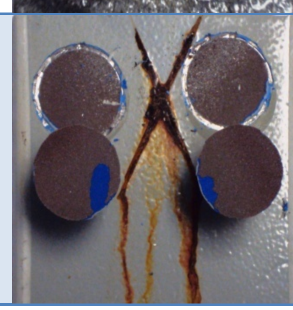
Figure 5.1 Primer Performance After 2000 (or 1500)-hour Salt Fog Test.

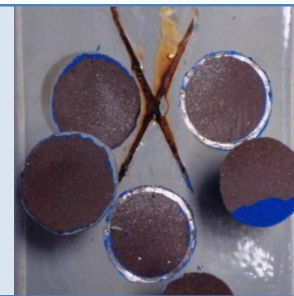
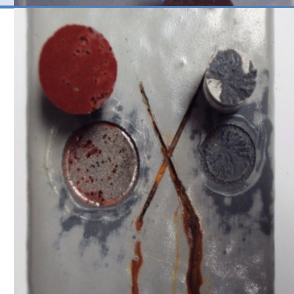
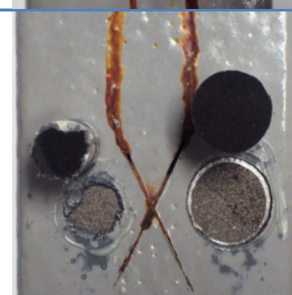
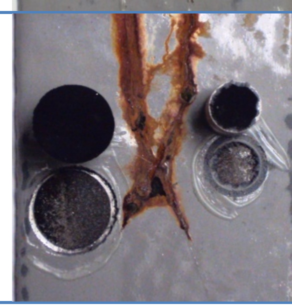
Figure 5.1 illustrates the salt fog resistent performance of several primers used in Phase I. Table 5.7 presents the adhesion results after 3000-hr of salt fog exposure. Within this table, the failure mode of the adhesion test is also reported. The primer for system G performed the best of all and there was no rust bleeding that occured at the scribe. Primer for system H1-02/H1-04 had a full blistering surface and large creepage at the scribe. However, system H1-04 performed very well due to the thick and tough topcoat. The primer without scarificial zinc corroded fast in the salt fog test, but was also able to give good protection if the topcoat can be properly selected.

It is important to test the full coating system when considering approval of a certain product. Contained within the appendix of this report includes the salt fog images for all systems at various cycle intervals. It can be concluded from both physical observations and testing that the stronger the primers were, the better the performance of the coating system was obtained.

Table 5.7 Adhesion Results after 3000-hr Salt Fog Exposure.

System code	Sub. System No.	Average adhesion strength (psi)	Failure mode	Photo of dollies
G1	01	450	1/2 cohesion within primer 1/2 cohesion within intermediate coat	
H1	01	995	40% cohesion within primer 40% cohesion within topcoat	
	02	436	adhesion between primer and topcoat	

	03	1334	Cohesion with topcoat	
	04	1326	50% adhesion with primer and substrate 50% adhesion with primer and topcoat	
A1	01	738	cohesion within primer	
P1	01	399	adhesion between primer and steel substrate	
N1	01	1005	adhesion between primer and intermediate coat	

	02	1020	90% cohesion with primer	
I1	01	613	adhesion between primer and substrate	
	02	798	adhesion between primer and substrate	
	03	424	adhesion between primer and substrate	

Figures 5.2 and 5.3 illustrate the effect of salt fog exposure in terms of the bond strength of each coating system in Phase I. The adhesion test results for as-received conditions are shown in section 5.7. The systems with zinc primer (either organic or inorganic) had less than 35% loss of the adhesion strength. There was almost no influence on bond strength of the H1-01 system which is inorganic zinc primer with a polysiloxane topcoat. It is difficult to say if the salt fog enhanced the bond strength of system H1-01 due to the difference and variance of plates in adhesion.

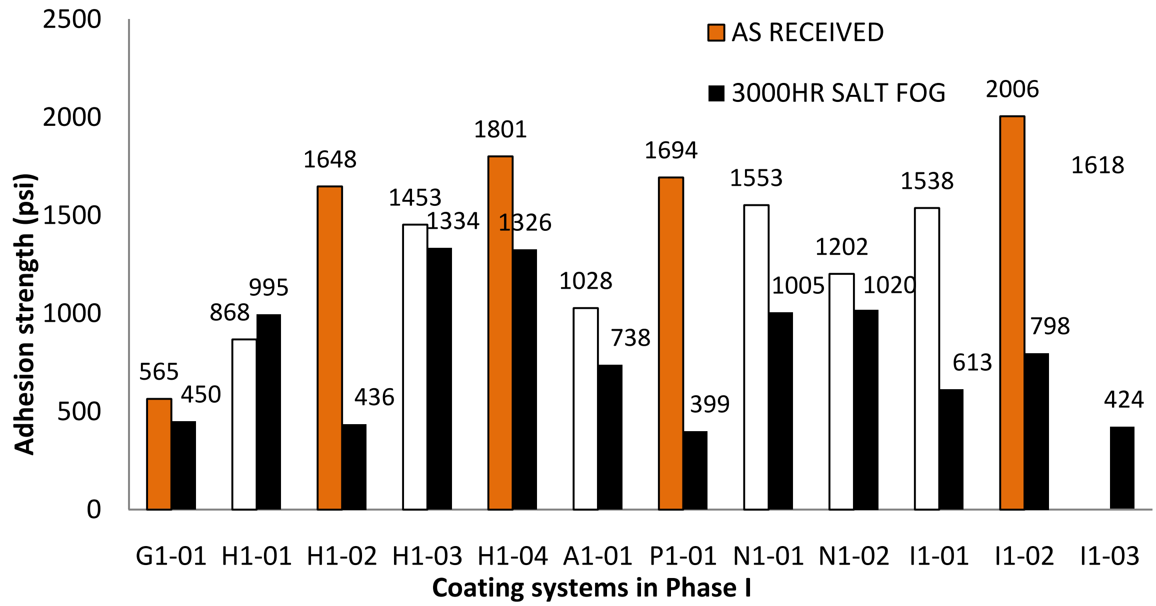


Figure 5.2 Adhesion Strength Chart (as Received and 3000-hour Exposure)

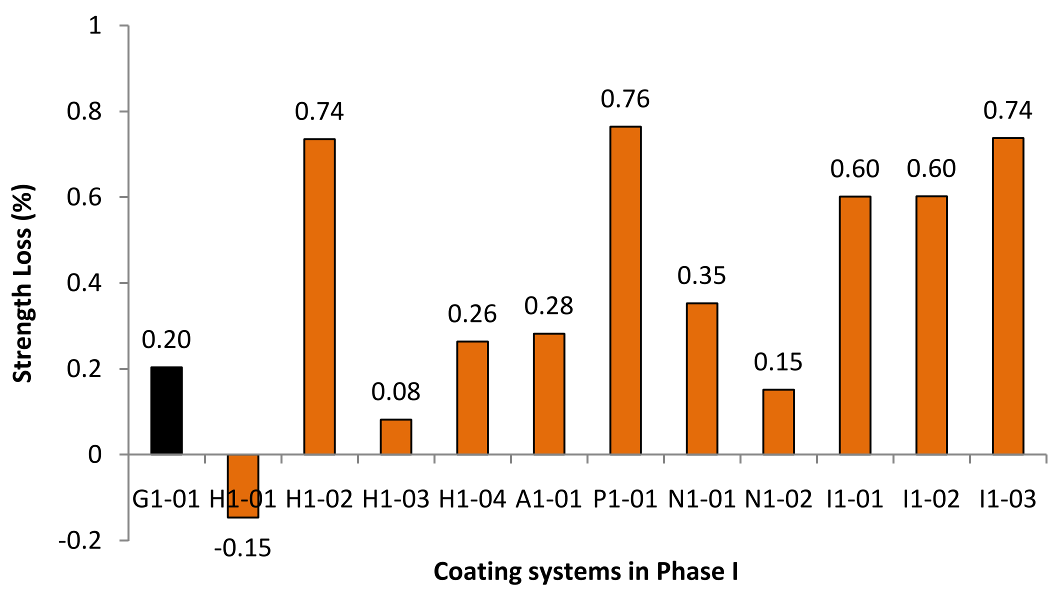


Figure 5.3 Adhesion Loss (as Received and 3000-hour Exposure)

System G (i.e. the baseline) exhibited a 20% adhesion loss, performing fairly well; however, the initial strength was relatively lower than other systems. System H1-02 and P1-01 had very high strength in adhesion before salt fog exposure; however, they were not really ideal coating systems in terms of salt induced corrosion.

5.3 QUV Weathering Test Results

The color change, ΔE, for each coating system was measured at every 500 hour interval. Appendix D shows all the photos taken during the test. The results reflect the UV resistance of different topcoat. Figure 5.4 details the ΔE values of coating systems in Phase one. Some coating types exhibited dramatic color change in the first 500-hour duration. After that, the color coordinates were maintained at a close range. The polyurea coatings formulated with aromatic isocyanates (aromatic polyurea) were vulnerable to UV damage and color loss. Table 5.8 presents the coating surface property change numerically. The test results show that the color change of system G was on the threshold of acceptance value of three (3).

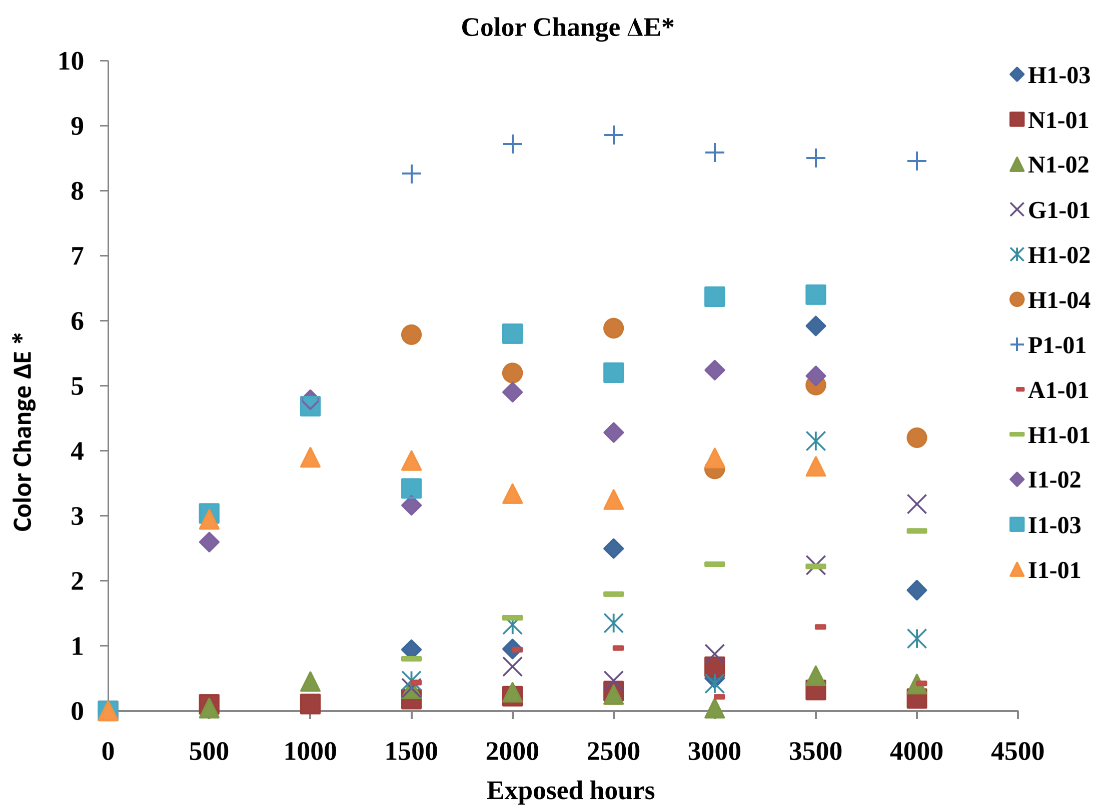


Figure 5.4 Color Change During the QUV Weathering Test.

As illustrated in Table 5.8 data, the polyaspartic coating (P1-01) maintained better color retention during the QUV weathering test. The gloss loss of system P1-01 was fairly low among the other coating system. System H1-04 and P1-01 had very large color and gloss change due to the intrinsic UV instability of aromatic polyurea polymers. Polyaspartic polyurea which was formulated with aliphatic polyurea had desirably aesthetic properties.

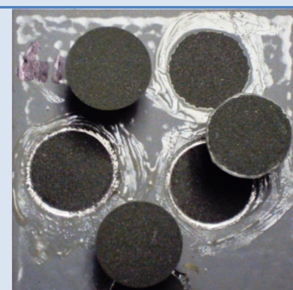
Table 5.8 Coating Surface Property Change by QUV Weathering.

Properties	System H1				A1	P1	N1		I1			G1
	01	02	03	04	01	01	01	02	01	02	03	01
ΔE (4000hr exposure)	2.27	1.11	1.86	4.2	0.42	8.46	0.32	0.54	3.89	5.24	6.37	3.18
Average Gloss Change (%)	33.6	7.14	9.90	98.4	22.4	85.5	23.6	1.07	N.A.[3]	N.A.	N.A.	93.9

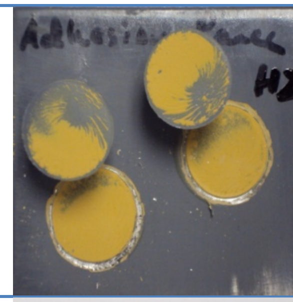
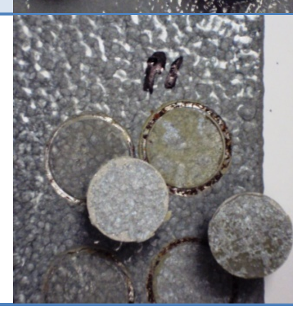
5.4 Adhesion Test Results

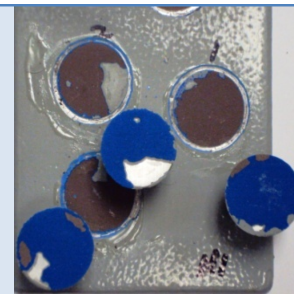
The results which include strength value, failure modes and photos are listed in Table 5.9.

Table 5.9 Adhesion Results (as Received).

System	Sub. System No.	Average adhesion strength (psi)	Failure mode	Photo of dollies
G1	01	565	cohesion within primer	
H1	01	868	1/2 cohesion within primer 1/2 cohesion within topcoat	

[3] The information was not available at printing.

H1	02	1648	70% cohesion within primer 30% adhesion between primer and topcoat	
	03	1453	cohesion within topcoat	
	04	1801	cohesion within topcoat	
A1	01	1028	cohesion within primer	
P1	01	1694	cohesion within topcoat	

N1	01	1553	90% adhesion between primer and intermediate coat	
	02	1202	adhesion between primer and intermediate coat	
I1	01	1538	cohesion within topcoat	
	02	2006	cohesion within topcoat	
	03	1618	cohesion within topcoat	

Bar charts presented in Figure 5.5 shows the adhesion strength of each coating system in Phase I. System G1-01 which is used currently by MoDOT had the lowest adhesion strength among the coating systems in Phase I. Compared with organic zinc primer in system G1-01, the coating systems with organic zinc primer possessed higher adhesion such as system A1-01, N1-01 and

N1-02. Both N1-01 and system G1-01 were three-coat systems with epoxy as intermediate coat and polyurethane as topcoat. It shows that the coating systems containing organic zinc primer had superior bonding ability to coating systems with inorganic zinc primer like system G1-01.

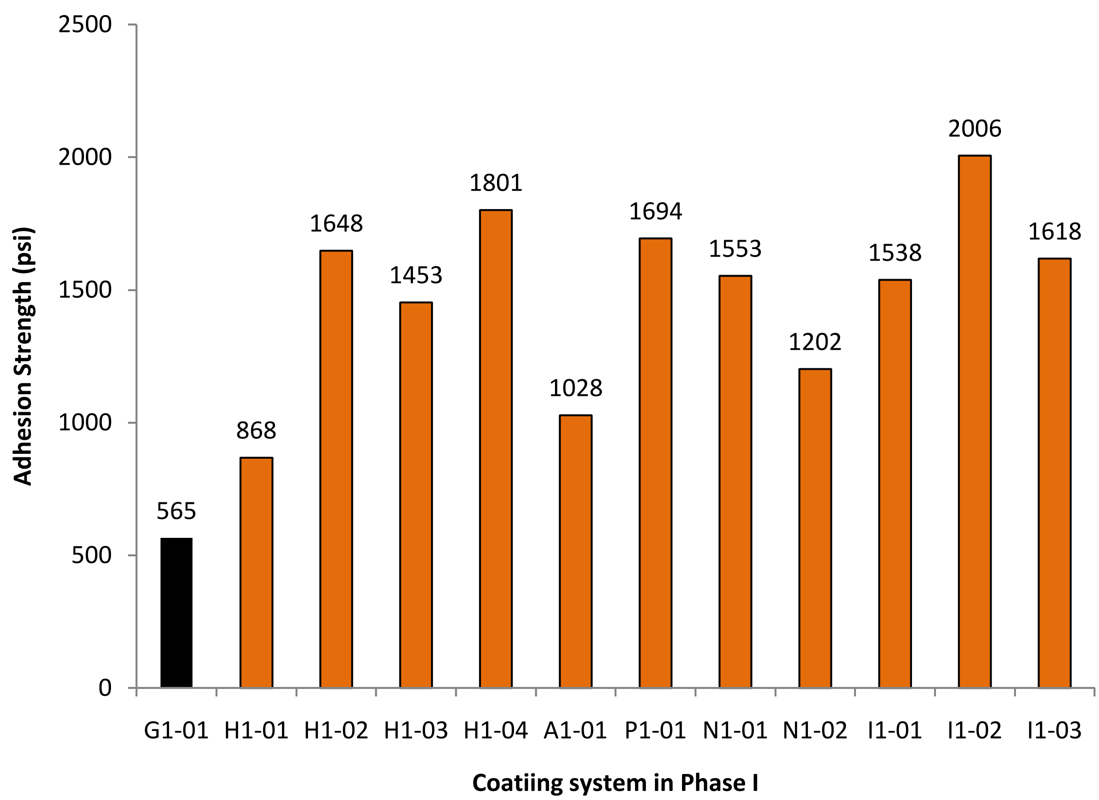


Figure 5.5 Adhesion Strength Chart (as Received).

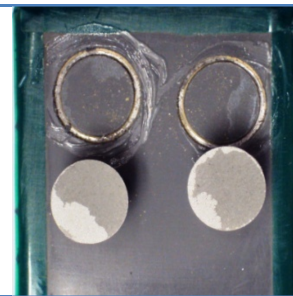
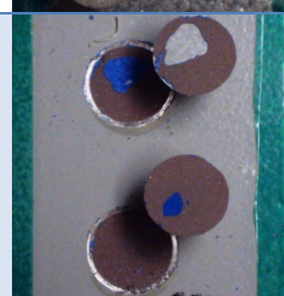
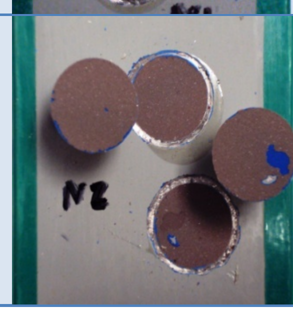
5.5 Freeze-thaw Test Results

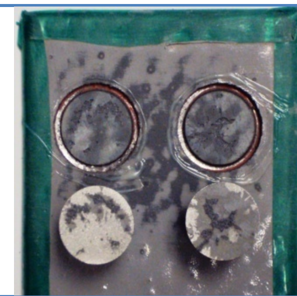
The adhesion tests were done after a 30-day cyclic freeze thaw test. The adhesion tests results are shown in Table 5.10 for phase I specimens. There was no obvious blistering or bleeding which occurred after the freeze-thaw testing.

Table 5.10 also indicates the failure mode location. Many systems possessed very good adhesion strength and resulted in cohesion within the primer coat system. The freeze-thaw stability test will influence the stress within the topcoat. From the pictures below, it may be observed that coating systems with polyurethane topcoat have the more adhesion loss caused by freeze-thaw cycling. System G had above 50% adhesion loss. According to the results, coating systems with topcoats such as polysiloxane, plyurea and fluoropolymer retain the adhesion strength at the same level even after 30-day freeze-thaw stability test.

Table 5.10 Adhesion Results after Freeze-thaw Test.

System	Sub. System No.	Average adhesion strength (psi)	Failure mode	Photo of dollies
G1	01	333	cohesion within primer	
H1	01	1082	1/2 cohesion within primer 1/2 cohesion within topcoat	
	02	1834	80% cohesion within primer 20% adhesion between primer and topcoat	
	03	1492	Cohesion within topcoat	

H1	04	2032	Cohesion within topcoat	
A1	01	815	cohesion within primer	
P1	01	1786	cohesion within topcoat	
N1	01	1176	adhesion between primer and intermediate coat	
	02	1230	adhesion between primer and intermediate coat	

I1	01	1554	Cohesion within topcoat	
	02	1670	Cohesion within topcoat	
	03	2269	Cohesion within topcoat	

Figures 5.6 and 5.7 summarize the system adhesion results and the retention levels.

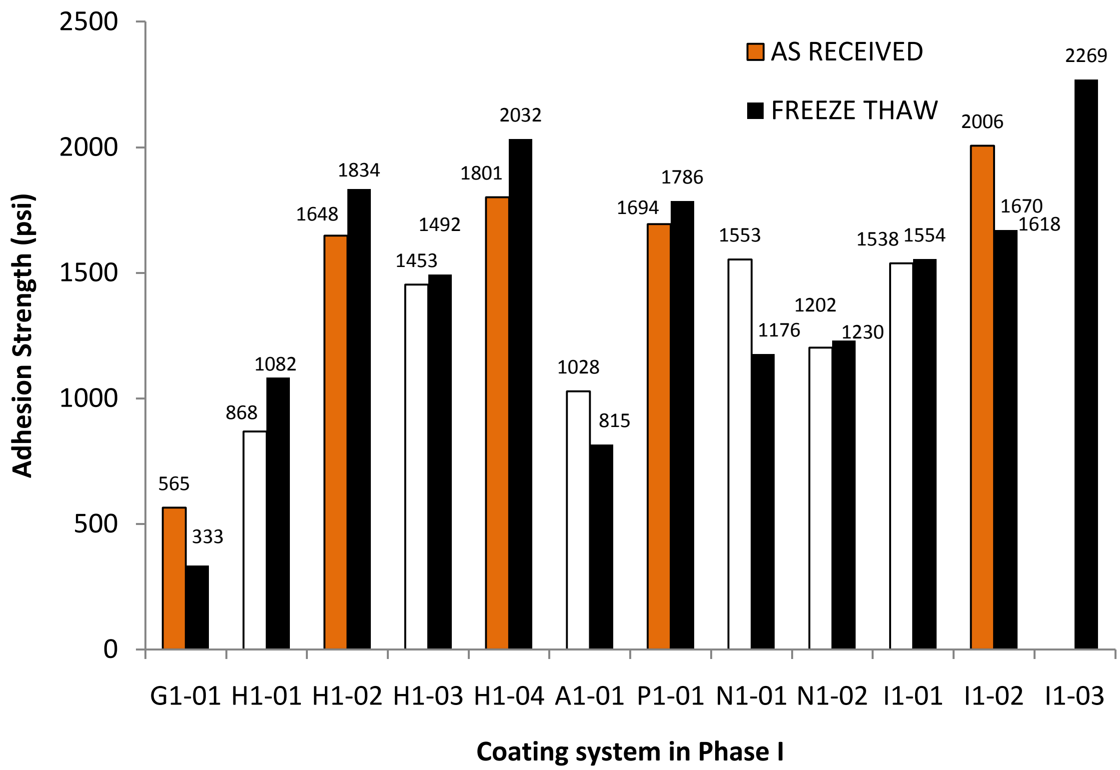


Figure 5.6 Adhesion Strength Chart (as Received and 3000-hour Exposure).

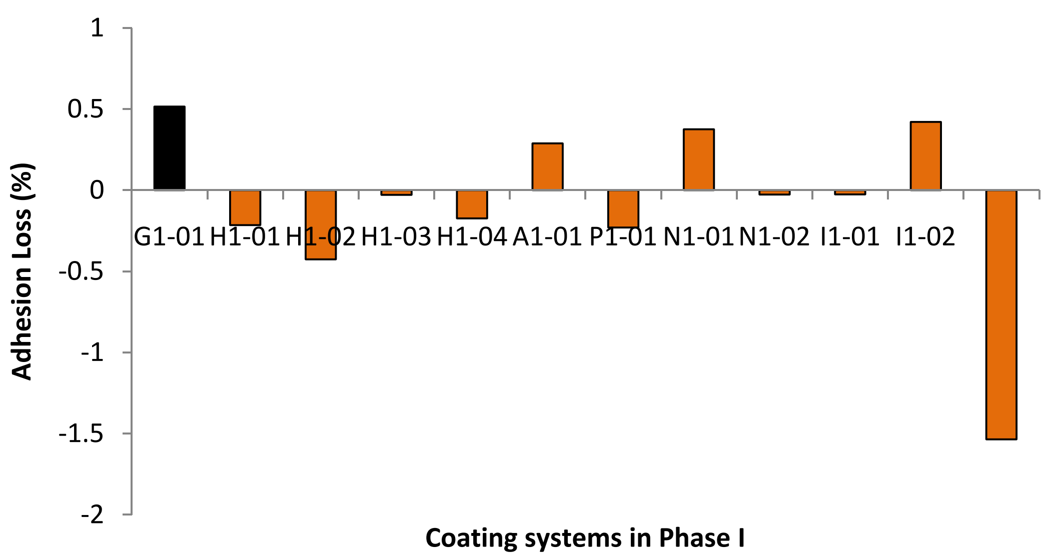


Figure 5.7 Adhesion Loss Chart (as Received and after Cyclic Freeze-thaw Stability Test).

5.6 Electrochemical Test

Table 5.11 reports the electrochemical tests of 5 coating systems in Phase I before and after 3000-hr salt fog exposure. Five coating systems were selected according to their early salt fog test performance. They were selected based upon the systems that showed the promising final application of coating systems for steel atmospheric corrosion protection.

The results indicated that the coating systems with inorganic (IOZ) vs. organic zinc (OZ) primers have lower potentials both before and after the salt fog exposure. This means more active materials sacrifice to protect the bare steel. The potentials (E_{corr}) of systems G1 and N1 remained below -1.00V. System A lowered the potential below -1.00V after salt fog. The results therefore indicate different mechanisms of corrosion process. It is worth noting that the performance of system H1-03 (ployurea/polyaspatic) remained rather consistent through the test. More detailed results are shown in Appendix E.

Table 5.11 Electrochemical Test Results.

System	E_{corr}(volts) (V vs. SHE)					Current Density(Amp/cm^2)				
	Before	Avg.	After	Avg.	E_{corr} Change (%)	Before	Avg.	After	Avg.	I change (%)
G1-01-I	-1.095	-1.106	-1.25	-1.185	7.19%	5.53E-05	5.32E-05	6.66E-05	6.97E-05	31.00%
G1-01-II	-1.115		-1.120			5.11E-05		7.28E-05		
H1-03-I	-0.811	-0.819	-0.873	-0.832	1.61%	2.39E-06	2.31E-06	3.78E-06	3.84E-06	66.53%
H1-03-II	-0.827		-0.792			2.22E-06		3.90E-06		
H1-04-I	-0.907	-0.896	-0.767	-0.766	-14.5%	5.02E-06	5.04E-06	1.93E-05	1.84E-05	265.6%
H1-04-II	-0.885		-0.766			5.07E-06		1.76E-05		
A1-01-I	-0.850	-0.841	-0.950	-0.991	17.77%	3.68E-06	3.84E-06	4.04E-05	4.16E-05	985%
A1-01-II	-0.832		-1.031			3.99E-06		4.29E-05		
N1-01-I	-1.064	-1.042	-1.069	-1.061	1.77%	3.36E-05	3.63E-05	6.02E-05	6.31E-05	73.63%
N1-01-II	-1.020		-1.052			3.90E-05		6.60E-05		
I1-02-I	-0.776	-0.792	-0.927	-0.993	25.41%	3.11E-06	3.00E-06	7.64E-05	7.84E-05	2514%
I1-02-II	-0.807		-1.059			2.89E-06		8.04E-05		

From the results shown in Tables 5.11 and 5.12, system N1-01 and system G1-01 had lower level of E_{corr} values due to the existence of zinc which has lower potential. These two coating systems showed the same corrosion mechanism. System G1-01 had a more stable corrosion rate condition (increase of 31%) while system N1-01 had an increase of 74% of the corrosion rate after salt fog exposure. However, system A1-01 showed a different pattern; namely, the E_{corr} values were maintained at a lower value which suggests a different corrosion mechanism.

Systems H1-03, H1-04 and I1-01 are the systems without zinc primer. The Values of E_{corr} were higher than those with zinc primer. The corrosion protection performance sequence is H1-03 > H1-04 > I1-01 after the 3000-hour salt fog test. This coincides with the results of corrosion rate calculation.

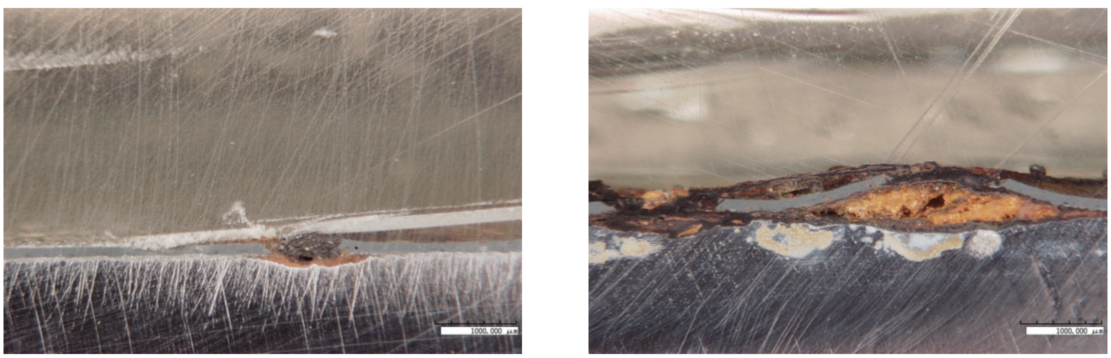
Table 5.12 Corrosion Rate Calculation

corrosion rate (average of duplicate tests) MPY-mils per year						
Conditions	H1-03	H1-04	A1-01	N1-01	G1-01	I1-02
As received	1.06	2.311	2.3	16.65	24.46	1.375
After 3000 hrs	1.7657	8.449	15.336	29.13	32.05	30.805

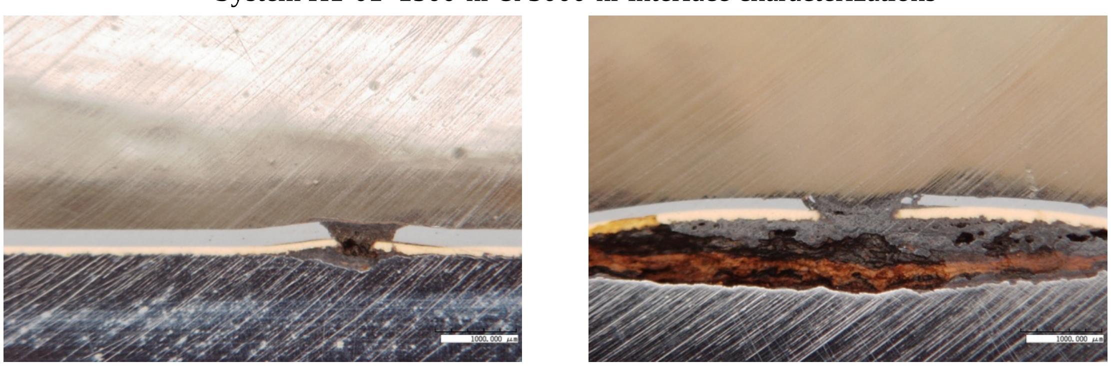
5.7 Interface Characterization

The interface characterization images are shown in Figure 5.8. Creepage was observed under the image capture system undertaken in this experimental phase of the study. Figure 5.8 shows partial results for three systems. The undercut can be seen clearly in these images under magnification. System A1, which performed very well in salt fog testing, showed no undercut underneath the coatings. However, images of system H1-04 and P1-01 exhibited significant corrosion products underneath the paint which caused the reduction of the coating adhesion.

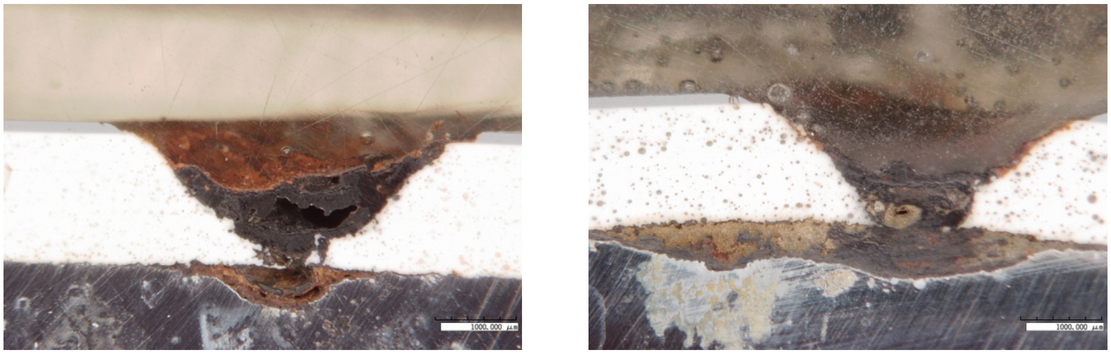
For system H1-01, the rust creepage grew fast underneath the coating. There was a large accumulation after inspecting the 3000 hr salt fog exposure plates. The coating system is a 3-component inorganic ethyl silicate zinc rich primer with polysiloxane topcoat. As shown in Figure 5.8, the rust creepage for system H1-02 grew fast underneath the primer which caused easy peeling of the primer from the substrate. The epoxy primer was not effective and durable in the salt induced corrosion environment. The primer for system A1-01 provided cathodic / sacrificial protection to the bare steel even over 3000 hr salt fog test. The corrosion was limited within an area shown in the image (see Fig. 5.8) by synergic action of micaceous iron oxide and zinc. Systems N1-0# did not perform as well as system A1-01. The rust creepage developed underneath the primer within a limited range. The zinc primers for systems N1-0# were not sacrificial enough. System G performed very well as expected. Observed for system A1-01, the inorganic zinc primer of system G acted as a cathode to protect the steel substrate from corrosion. Systems I1-0# used urethane primers. They did not perform very well in salt fog test. The rust creepage grew fast underneath the coating systems.



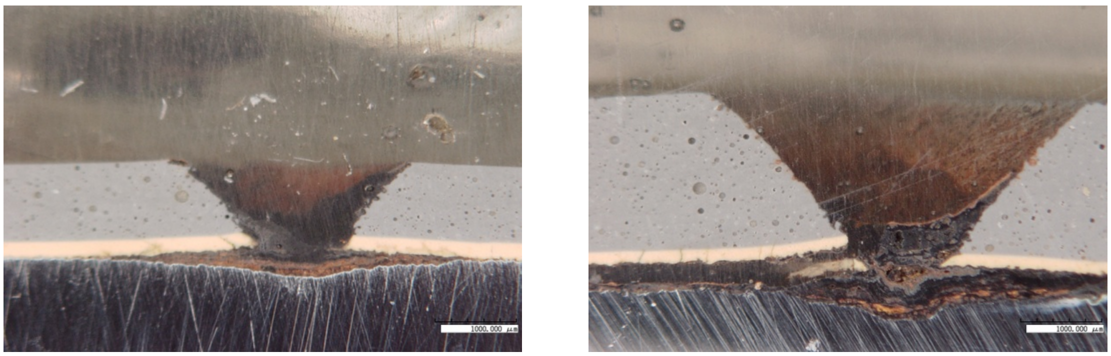
System H1-01 1500-hr & 3000-hr interface characterizations



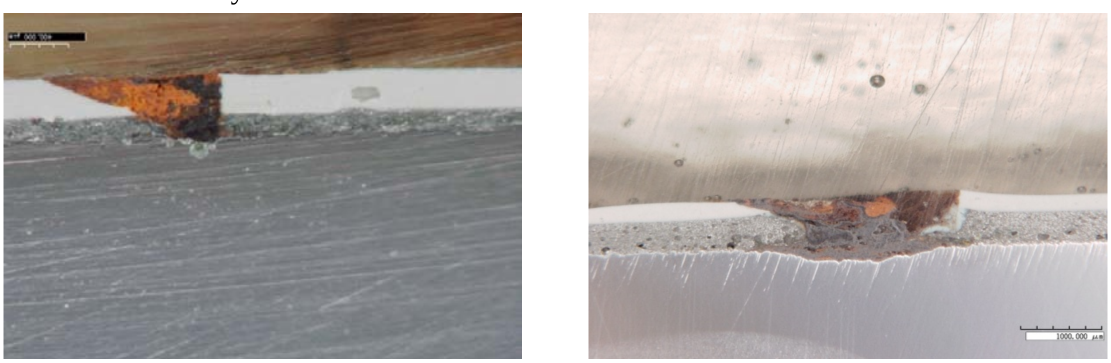
System H1-02 1500-hr & 3000-hr interface characterizations



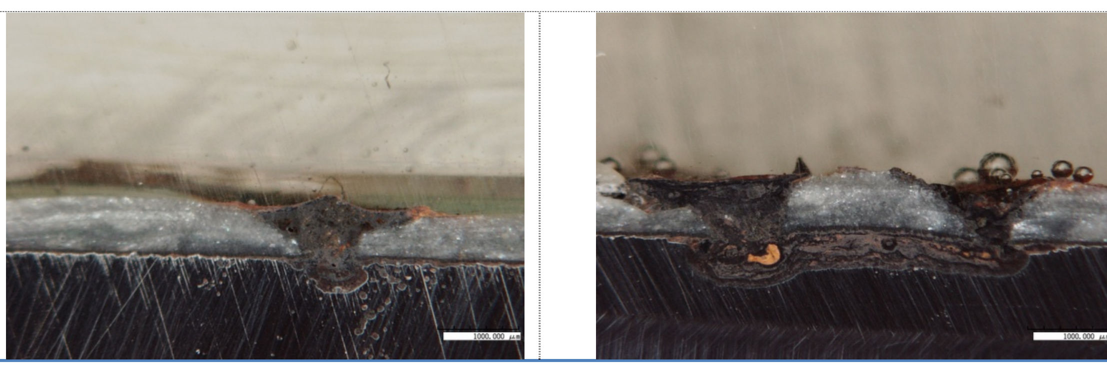
System H1-03 1500-hr & 3000-hr interface characterizations



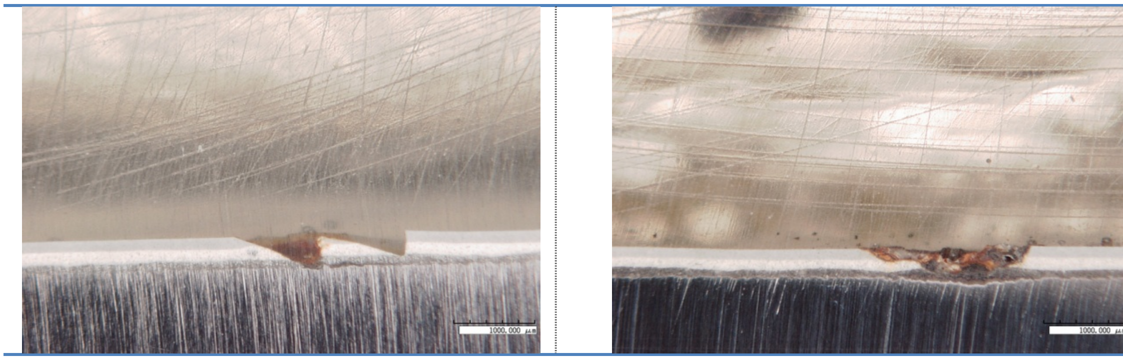
System H1-04 1500-hr & 3000-hr interface characterizations



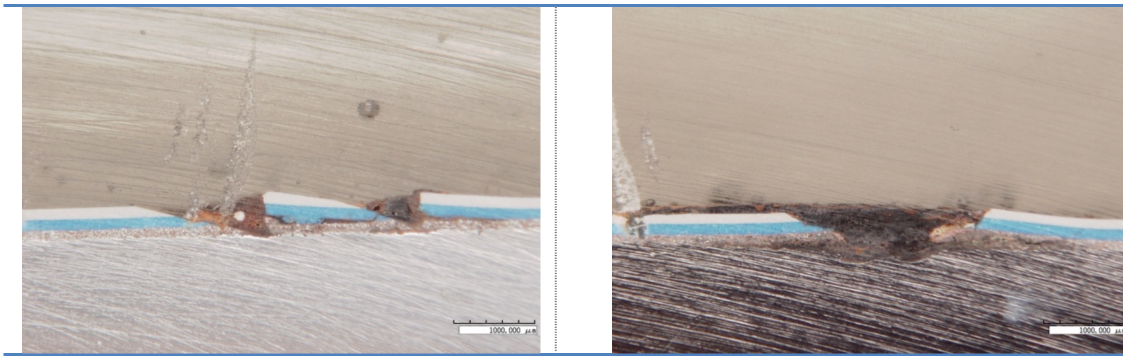
System A1-01 1500-hr & 3000-hr interface characterizations



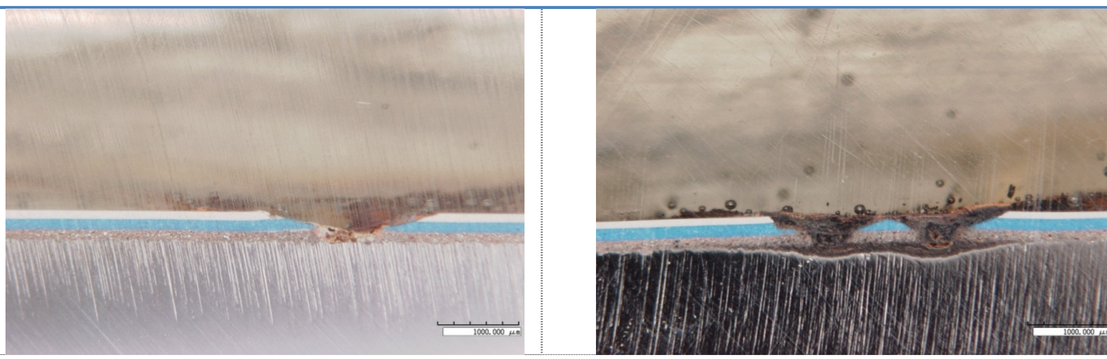
System P1-01 1500-hr & 3000-hr interface characterizations



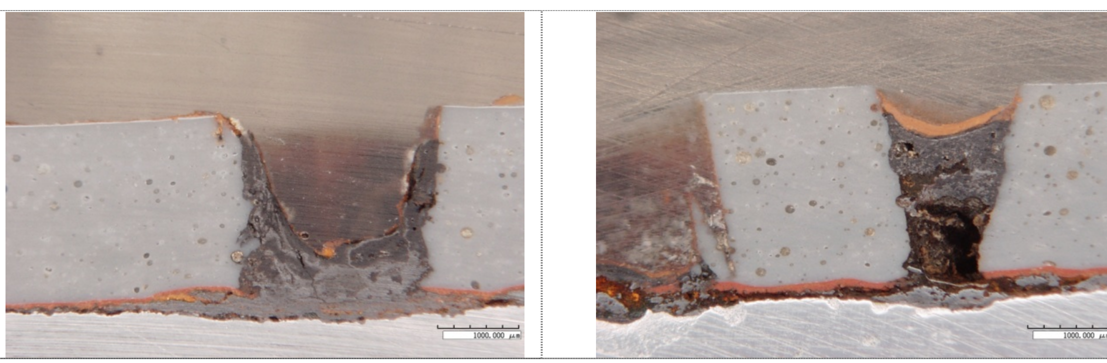
System G1-01 1500-hr & 3000-hr interface characterizations



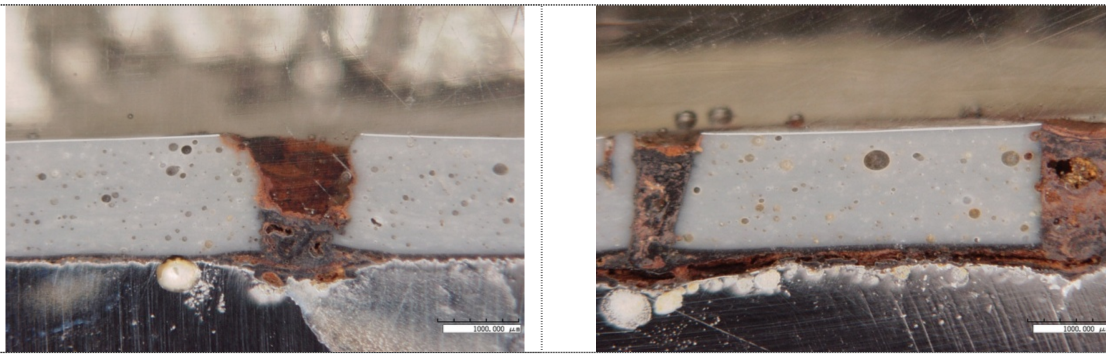
System N1-01 1500-hr & 3000-hr interface characterizations



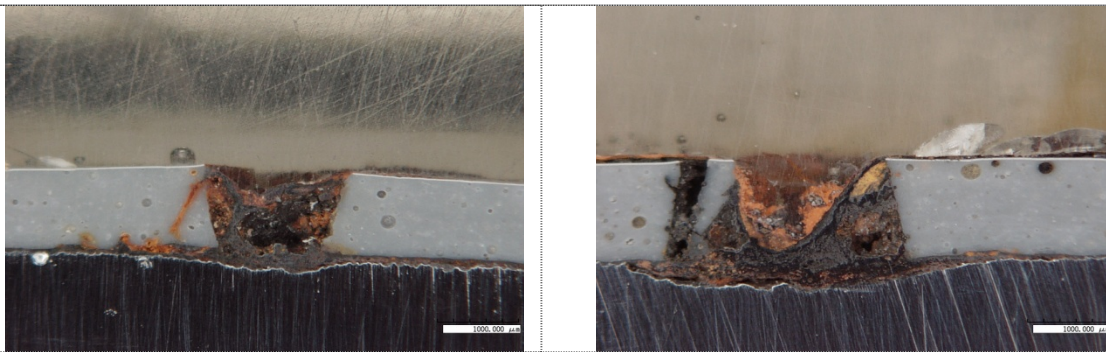
System N1-02 1500-hr & 3000-hr interface characterizations



System I1-01 1500-hr & 3000-hr interface characterizations



System I1-02 1500-hr & 3000-hr interface characterizations



System I1-03 1500-hr & 3000-hr interface characterizations

Figure 5.8 Interface Characterization for Each System.

5.8 Phase II Results

Results for the Phase II Lead-based paint overcoating will be reported when testing evaluations are completed. A separate document will follow to report Phase II results and recommendations.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 New Coating and Recoating Systems

The summary of Phase I results is shown in Table 6.1. Systems were grouped into performance categories of *excellent*, *good*, *fair,* or *poor* based upon visual inspection and/or performance data depending on the specific performance test and information / data gathered.

- The coating systems evaluated in Phase I have their advantages and disadvantages in terms of the performance on different tests. A case in point is system G, currently used by MoDOT, that performs excellent (E) in the salt-fog test, but only fair (F) in the freeze thaw stability exhibiting lower results than other coating systems. Polyurea type coatings are very good at producing bond strength, but its salt induced corrosion inhibition is not as strong as the systems with high solid zinc primer. There is not one panacea for all the conditions as shown in Table 6.1. It is of importance to make a case-by-case study when making the decision on which type of paints to use and in what field location / exposure.
- Inorganic (IOZ) vs. organic zinc (OZ) primers: NEPCOAT accepts both the organic and inorganic zinc-rich primer coating as its qualified product. In MoDOT, only IOZ is allowed to be used. The acceptance criteria for IOZ and OZ are 350 psi and 600 psi respectively in terms of the minimum pull-off strength. It coincides with the test results in phase I. This means when adhesion is a key consideration for paint selection, the OZ primer is supposed to be a better choice due to its better adhesive strength to avoid peeling-off.
- The performance of system A1-01 in phase I shows the promising application of coating system-micaceous iron oxide zinc primer with aliphatic polyurea polyaspartic topcoat. It has almost equal performance in terms of salt-fog resistance compared to system G, but provides the added feature of superior UV resistance (E) with good (G) freeze-thaw stability.
- Among the polyurea coating systems, the aromatic polyurea coatings shows the drawback on UV resistance, like system H1-04 which gives good (G) corrosion inhibition, but only fair (F) UV stability. The impressive properties of polyurea coatings are no sag, nearly zero VOC and ease of application. They are usually tough, chemical resistant and pretty thick compared to conventional coatings used on steel bridges. The coating system H1-03 with a polyaspatic topcoat shows better (G) UV resistance. Aromatic polyurea can be

considered to be used at locations where aesthetic appearance (color) is not the first consideration, for example inside surfaces of steel box girders.

Table 6.2 provides material costs at the time of printing provided by surveyed vendors. It is important to note that this cost data was simply the surveyed material costs when purchased in a "large quantity" and do not consider installation or life-cycle costs. Some systems, which are two-coat systems, would be expected to have reduced installation costs compared to similar counterpart three-coat systems. One system may be more applicator friendly than another and thereby result in reduce application costs. Furthermore, when the life-cycle history of the system is considered a more expensive initial system could be more cost effective if the maintenance is low and the life of the coating system is long. All of these issues should be considered in the decision making process when a system is selected for field use.

Table 6.1 Summary of Performance of Coating Systems for New Structural Steel.

Coating system code	Accelerated lab test			Adhesion Strength (psi)	Electrochemical tests
	Salt fog resistant test	QUV weathering	Freeze thaw stability		
G1-01	E	G	F	565	E
H1-01	F	G	E	868	N.A.[4]
H1-02	P	G	E	1648	N.A.
H1-03	G	G	G	1453	G
H1-04	G	F	E	1801	F
A1-01	E	E	G	1028	E
P1-01	P	P	E	1694	N.A.
N1-01	E	E	F	1553	G
N1-02	E	E	G	1202	N.A.
I1-01	F	F	G	1538	N.A.
I1-02	G	F	F	2006	F
I1-03	F	F	E	1618	N.A.
E-Excellent G-Good F-Fair P-Poor					

[4] The information was not available at printing.

Table 6.2 Unit Cost for Each Coating Material.

System code	Primer		Intermediate coat		Topcoat		Total
	$/ mixed gallon	$/ ft^2 at recommended DFT	$/ mixed gallon	$/ ft^2 at recommended DFT	$/ mixed gallon	$/ ft^2 at recommended DFT	$/ ft^2 at total recommended DFT
System G	$45.00/gal	$0.1031/$ft^2$ at 3 mils DFT	$32.00/gal	$0.0798/$ft^2$ at 3 mils DFT	$45.00/gal	$0.1751/$ft^2$ at 5 mils DFT	0.35/ft^2
H1-01	$55.37/gal	$0.0908/$ft^2$ at 2 mils DFT	[redacted]	[redacted]	$110.39/gal	$0.343/$ft^2$ at 5 mils DFT	0.434/ft^2
H1-02	$35.10/gal	$0.0912/$ft^2$ at 3 mils DFT	[redacted]	[redacted]	$95.15/gal	$0.59/$ft^2$ at 5 mils DFT	0.682/ft^2
H1-03	$42.74/gal	$1.327/$ft^2$ at 50 mils DFT	[redacted]	[redacted]	$95.15/gal	$0.59/$ft^2$ at 5 mils DFT	1.917/ft^2
H1-04	$35.10/gal	$0.0912/$ft^2$ at 3 mils DFT	[redacted]	[redacted]	$42.74/gal	$1.327/$ft^2$ at 50 mils DFT	1.418/ft^2
A1-01	$58.00/gal	$0.1751/$ft^2$ at 3 mils DFT	[redacted]	[redacted]	$100.00/gal	$0.4615/$ft^2$ at 6 mils DFT	0.64/ft^2
P1-01	$46.65/gal	$0.187/$ft^2$ at 6 mils DFT	[redacted]	[redacted]	$80.40/gal	$2.68/$ft^2$ at 50 mils DFT	$2.867/$ft^2$
N1-01	$67.95/gal	$0.202/$ft^2$ at 3 mils DFT	$44.85/gal	$0.251/$ft^2$ at 6 mils DFT	$92.50/gal	$0.248/$ft^2$ at 4 mils DFT	0.782/ft^2
N1-02	$67.95/gal	$0.202/$ft^2$ at 3 mils DFT	$44.85/gal	$0.251/$ft^2$ at 6 mils DFT	$355.00/gal	$0.923/$ft^2$ at 2 mils DFT	1.32/ft^2
I1-01	N.A.[5]	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
I1-02	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
I1-03	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.

[5] The information was not available at printing.

6.2 Overcoating Systems

Conclusions and recommendations for Phase II Lead-based paint overcoating will be reported when all the testing evaluations are completed. A separate document will follow to report Phase II results and recommendations.

7. IMPLEMENTATION PLAN

A recoating and/or overcoating implementation plan has been put forward to demonstrate the outcome of this research project. System A1-01 is recommended by the research team for application to a recoating and/or overcoating project involving an existing Missouri Department of Transportation bridge structure due to its excellent performance in the lab tests. The bridge selection and application process are currently being discussed with MoDOT for implementation following this reporting phase of study.

8. REFERENCES

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