ASSESSMENT OF WEATHERING STEEL BRIDGE PERFORMANCE IN IOWA AND DEVELOPMENT OF INSPECTION AND MAINTENANCE TECHNIQUES

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16 Abstract

Weathering steel is commonly used as a cost-effective alternative for bridge superstructures, as the costs and environmental impacts associated with the maintenance/replacement of paint coatings are theoretically eliminated. The performance of weathering steel depends on the proper formation of a surface patina, which consists of a dense layer of corrosion product used to protect the steel from further atmospheric corrosion. The development of the weathering steel patina may be hindered by environmental factors such as humid environments, wetting/drying cycles, sheltering, exposure to de-icing chlorides, and design details that permit water to pond on steel surfaces.

Weathering steel bridges constructed over or adjacent to other roadways could be subjected to sufficient salt spray that would impede the development of an adequate patina. Addressing areas of corrosion on a weathering steel bridge superstructure where a protective patina has not formed is often costly and negates the anticipated cost savings for this type of steel superstructure. Early detection of weathering steel corrosion is important to extending the service life of the bridge structure; however, written inspection procedures are not available for inspectors to evaluate the performance or quality of the patina. This project focused on the evaluation of weathering steel bridge structures, including possible methods to assess the quality of the weathering steel patina and to properly maintain the quality of the patina. The objectives of this project are summarized as follows:

- Identify weathering steel bridge structures that would be most vulnerable to chloride contamination, based on location, exposure, environment, and other factors.
- Identify locations on an individual weathering steel bridge structure that would be most susceptible to chloride contamination, such as below joints, splash/spray zones, and areas of ponding water or debris.
- Identify possible testing methods and/or inspection techniques for inspectors to evaluate the quality of the weathering steel patina at locations discussed above.
- Identify possible methods to measure and evaluate the level of chloride contamination at the locations discussed above.
- Evaluate the effectiveness of water washing on removing chlorides from the weathering steel patina.
- Develop a general prioritization for the washing of bridge structures based on the structure’s location, environment, inspection observations, patina evaluation findings, and chloride test results.

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TABLE OF CONTENTS

Appendix A — Bibliography
Appendix B — Inventory of Weathering Steel Bridges in Iowa
Appendix C — Field Sheet Summaries
Appendix D — Chloride Testing and Lab Results
Appendix E — SEM/EDS, FTIR, and XRD Lab Test Results
Appendix F — Proposed Field Inspection Ratings

ASSESSMENT OF WEATHERING STEEL BRIDGE PERFORMANCE IN IOWA AND DEVELOPMENT OF INSPECTION AND MAINTENANCE TECHNIQUES

INTRODUCTION

The Bridge Maintenance and Inspection Unit of the Iowa Department of Transportation (Iowa DOT) has expressed a desire to evaluate the performance of weathering steel bridge structures, including possible methods to assess the quality of the weathering steel patina on bridge superstructures and to properly maintain the quality of the patina in deicing salt environments. This project developed a scope of work to inspect various weathering steel bridges in Iowa in order to develop potential inspection and/or testing methods to evaluate patina performance and chloride contamination. Possible benefits from routine bridge washing were also evaluated.

BACKGROUND

Weathering Steel Materials

Under the right conditions, weathering steel will form a protective oxide coating that will eliminate the need for future painting. The oxide layer, or patina, is typically dense and well-adhered to the base metal, reducing the penetration of moisture, oxygen, and other corrosive contaminants. This protective patina thus reduces long-term corrosion rates. By eliminating the need for painting, the lower life-cycle costs of weathering steel structures provide an advantage over standard painted steel structures.

Weathering steel evolved in the 1930's, when United States Steel Corporation acquired various patents for high-strength low-alloy steel products. By alloying the steel with different elements, particularly copper, it was found that the corrosion resistance of the steel was improved, virtually eliminating the need for painting. In addition, the alloys resulted in an increased yield strength of the steel products. Marketed under the name "Cor-Ten," United States Steel Corporation's weathering steel products were first used in various applications, including coal-hopper cars, barges, transmission towers, and trolley cars. Recognizing the benefits of improved atmospheric corrosion resistance and higher strength, several other steel companies developed forms of weathering steel. Although "Cor-Ten" is the most recognizable, other weathering steel products included "Mayari R" by Bethlehem Steel Corporation and "Yolloy" by Youngstown Steel.

Initially introduced in 1968, ASTM A588 Grade 50W (AASHTO M222) covered weathering steel products comprised of typical mild steel alloyed with 2% or less of various elements, including copper, phosphorus, chromium, nickel, and/or silicon. In 1974, ASTM A709 Grade 50W (AASHTO M270) was introduced to cover corrosion resistant steels for use in bridges. By alloying steels with copper or other selected elements, it was found that the corrosion resistance increased to approximately four times that of structural carbon steel without copper.

History of Weathering Steel Bridges

In the 1960's and 1970's, weathering steel was commonly viewed as a "maintenance-free" cost-effective alternative for bridge superstructures, as the costs and environmental impacts associated with the maintenance/replacement of paint coatings would be theoretically eliminated. Weathering steel was first used for bridge applications in 1964, when weathering steel bridges were constructed in Michigan, Iowa and New Jersey. During the late 1970's, Michigan evaluated many of their weathering steel bridges and found that the protective patina had not formed and the corrosion rates were not reduced. As a result, Michigan instituted a partial moratorium on weathering steel bridges in 1979. It focused on avoiding weathering steel in urban and industrial areas, as well as low-clearance, tunnel-like environments. In 1980, the moratorium was expanded to include all weathering steel bridges. However, by this time Michigan had already constructed approximately 500 bridges using weathering steel.

After the Michigan moratorium, many states followed suit by limiting or eliminating weathering steel bridges going forward, often stopping short of banning their use outright. The most common reasons for the limitations were the problems reported by Michigan or other states, and/or similar conditions observed within their own state.

By the mid-1980's, approximately 2,000 weathering steel bridge structures had been constructed in the United States. A decade later, the number had only increased by approximately 300 structures, indicating that many agencies had reservations regarding their use. The perceived problems with the use of weathering steel for bridge structures resulted in the initiation of several research projects during the 1980's and 1990's.

In the early 1980's, a task group was formed with the support of the American Iron and Steel Institute (AISI) that included federal highway officials, state bridge engineers, and corrosion specialists. This task group performed a field investigation of approximately 49 bridges in seven states (Michigan, Illinois, Maryland, New York, North Carolina, Wisconsin, and New Jersey) in order to evaluate the performance of weathering steel bridges in different environments. This study found that the performance of most weathering steel bridges was either "good" or "good with moderate corrosion in some areas." Approximately 12% of the bridges inspected had "heavy" corrosion in some areas and deicing salts were found to be a major contributor to the excessive corrosion.

In 1984, the National Cooperative Highway Research Program (NCHRP) set out to document the state of the practice, evaluate the performance of weathering steel to date, and develop practical guidelines for design, construction, maintenance, and rehabilitation. The findings of this study are presented in NCHRP Report 272. Around the same time, a Michigan study identified several weathering steel bridges where a fine-grained brownish-black patina had not formed; instead the surface consisted of large delaminating flakes or thick exfoliating rust layers. Each of these studies identified examples of weathering steel bridge structures that may not have been used in appropriate environments. Particularly, the studies noted that weathering steel was not always "maintenance-free" and extended periods of wetness and heavy exposure to deicing salts caused the weathering steel to be vulnerable to ongoing, advanced corrosion.

In 1988, the FHWA sponsored a forum on weathering steel to bring together owners, designers, suppliers, fabricators, researchers, and maintenance personnel to examine the state of the art and develop guidelines on the proper use and maintenance of weathering steel. Subsequently, FHWA issued a Technical Advisory in 1989 providing guidelines for weathering steel use and maintenance. In addition, NCHRP issued Report 314, which served as a comprehensive summary of weathering steel properties, guidelines for use, and recommendations for inspection and maintenance. In general, the research revealed that weathering steel performed satisfactorily in the right environments with proper detailing. This finding resulted in renewed interest in the use of the material. Currently, it is reported that 40% to 45% of bridges are being built with some form of weathering steel.

The renewed interest in weathering steel bridge structures has also resulted in ongoing research on the topics of patina performance, inspection, and maintenance. Recent research in Japan has reiterated that chloride ions accelerate the growth of the rust layer and increase the rust particle size, which is not beneficial to the formation of a protective patina. In addition, Japan evaluates the appropriateness of a weathering steel bridge environment based on distance from the sea, which is essentially a measure of potential exposure to airborne chlorides. Because Japan recognizes that chloride contamination is a primary factor influencing weathering steel performance, it has also conducted research to determine if bridge washing helps to remove these chlorides and extend the life of weathering steel bridges.

Investigations in the United States have caused some agencies to adopt more robust inspection and maintenance requirements. For example, the New York State Department of Transportation (NYSDOT) has implemented a routine maintenance program to wash certain bridges annually and has developed inspection techniques to help inspectors evaluate the performance of the protective patina. Current research in this country includes an effort to develop types of “super weathering steels” to improve corrosion resistance while maintaining other material properties, such as toughness.

Weathering Steel Bridges in Iowa

The first weathering steel bridge in Iowa, which carried Iowa 28 over the Raccoon River, was constructed by the City of Des Moines in 1964. This structure was also one of the first applications of weathering steel for bridges in the United States. Between 1964 and 1972, four additional bridges were constructed that were owned by the Iowa DOT, with several others built by city and county agencies. Following the discovery of advanced deterioration in Michigan, the Iowa DOT discontinued the use of weathering steel bridges around 1980. During this time, the Iowa 28 bridge over the Raccoon River was re-inspected and it was found that the use of deicing salts accelerated the corrosion process. Areas of flaky rust and chloride contamination were observed at various locations where the protective patina did not form. In the mid-1980’s, this structure was painted to slow the observed weathering steel corrosion rates. Inspection of the four remaining Iowa DOT structures revealed that the protective patina was performing satisfactorily.

Based on the FHWA Technical Advisory and evaluations of the bridges in Iowa, the use of weathering steel was again implemented in the mid-1990’s. Currently, the Iowa DOT owns approximately 139 separately identified weathering steel bridge structures, and approximately 97 percent of these structures were constructed after 1994. A map of the weathering steel structures in Iowa is shown in Figure 1 and a list of these structures is included as Appendix B.

During the last several years, the Iowa DOT has found that chloride contamination is resulting in corrosion due to the lack of formation of an adequate patina. The chlorides appear to be present in the weathering steel patina as a result of the steel being in the “splash/spray zone” over other roadways or being in the “splash/spray zone” for adjacent bridge structures.

PROBLEM STATEMENT

Weathering steel bridges constructed over or adjacent to other roadways can be subjected to sufficient salt spray to impede the development of an adequate patina. Remediation of corroding weathering steel is typically difficult and costly. Early detection of weathering steel corrosion is important to extending the service life of the bridge structure; however, written inspection procedures are not available for inspectors to evaluate the performance or quality of the patina.

In addition, various transportation agencies believe that frequent bridge washing may help to extend the service life of weathering steel bridge structures. While the long-term benefits of washing are unknown, it is often perceived as a method to reduce the chloride contamination on the surface of the weathering steel patina. Currently, practical and reliable testing methods do not exist to determine the level of chloride contamination in the protective patina. As a result, it is unclear what level of chloride contamination is detrimental to patina performance, and this information would be helpful to prioritize the need for washing these structures.

Project Objectives

The objectives of this project are summarized as follows:

- Identify weathering steel bridge structures that are most vulnerable to chloride contamination, based on location, exposure, environment, and other factors. These bridges are more likely to exhibit unsatisfactory performance of the weathering steel patina.
- Identify locations on an individual weathering steel bridge structure that are most susceptible to chloride contamination, such as below joints, splash/spray zones, and areas of ponding water or debris.
- Identify possible testing methods and/or inspection techniques for inspectors to evaluate the quality of the weathering steel patina at locations discussed above.
- Identify possible methods to measure and evaluate the level of chloride contamination at the locations discussed above.
- Evaluate the effectiveness of water washing on removing chlorides from the weathering steel patina.
- Develop a general prioritization for the washing of bridge structures based on the structure's location, environment, inspection observations, patina evaluation findings, and/or chloride test results.

Scope of Work

The objective of this work was to identify inspection procedures, physical testing methods, and other evaluation techniques to assess the performance of a weathering steel patina. The intent is to ultimately utilize these techniques to establish maintenance protocols and schedules for the Iowa DOT weathering steel bridge inventory. These techniques were field tested on a sampling of weathering steel bridges in Illinois and Iowa. Also, as part of the review work, literature on bridge cleaning methods was reviewed to develop a pilot maintenance procedure for washing weathering steel bridges in an effort to reduce chloride contamination. The objective of the program was accomplished within the following tasks:

1. ***Document Review:*** A review of available literature on weathering steel performance, performance criteria, past problems, inspection methods, and maintenance techniques was performed. The literature review included studies and maintenance specifications from various state DOTs and other countries. Specific attention was focused on successful and unsuccessful in-situ evaluation techniques that have been employed to date, including visual and physical testing methods. Proprietary test methods to measure chloride contamination also were reviewed.

2. ***Assessment of Methods for Patina Evaluation and Chloride Testing:*** Commercially available test methods to measure chloride contamination of weathering steel were reviewed for suitability in this type of application. This review included the CHLOR*TEST, which has already been

utilized by Iowa DOT to measure chloride contamination in the field. Trial tests using the selected methods were performed to determine the ease of testing, relative accuracy, and repeatability. In addition, various methods to evaluate the condition of a weathering steel patina were reviewed. These methods include close-up visual inspection of the patina using a 10x magnifying lens, and tape and scrape tests to evaluate the adhesion between the patina and the steel substrate.

3. ***Selection of Field Trial Locations:*** Working with Iowa DOT, WJE selected various weathering steel bridge superstructures in Iowa for field investigation based on a review of the inventory and consideration of factors such as location, environment, condition rating, age, and traffic below the bridge. Whenever possible, the bridge structures were grouped geographically to reduce inspection costs. Initially, ten structures were envisioned for the field evaluations; however, this number was increased to thirty-one separately identified structures due to the inclusion of selected side-by-side structures and the close proximity of weathering steel bridges in the Des Moines area. The structures finally chosen were spread throughout approximately twelve different locations/environments. In addition to the structures in Iowa, trial field inspection and testing techniques were evaluated on six pedestrian bridges in Illinois in various environments.

4. ***Field Inspection and Testing:*** Based on the findings of the literature review and the trial inspection techniques, field inspection and testing of the selected Iowa weathering steel bridge superstructures was performed. At each structure, a brief visual survey of the superstructure was completed to determine the overall condition of the weathering steel and to identify possible locations where the weathering steel patina may not be performing as expected. Based on the visual survey, selected areas of the superstructure were identified for close-up inspection and chloride contamination testing. Physical test methods, determined from Tasks 1 and 2, were also performed. The performance of the weathering steel patina, including color of the rust and size of the scale, were documented in detail with close-up photographs of the patina. In order to evaluate the effectiveness of water washing on removing chlorides from the weathering steel patina, localized areas of selected bridge structures were washed during the Iowa field investigation. Chloride testing and patina evaluation were performed at selected areas after washing.

5. ***Review of Field Trial Findings:*** Inspection observations, evaluation findings, photographs, and chloride test results obtained during the field inspection were reviewed to categorize the site conditions, exposure, design details, and weathering steel performance at each bridge structure. The effectiveness of various evaluation techniques and test methods was reviewed. These findings were used to identify general correlations between the performance of the weathering steel and potential factors that may affect the satisfactory development of a patina.

6. ***Summary Report:*** Following completion of the tasks outlined above, this report was prepared to summarize the findings of the literature review, field inspection, and testing. In line with the project objectives discussed above, this report focuses on possible inspection/testing methods to evaluate weathering steel performance, performance criteria, identifying vulnerable locations in a bridge superstructure, and potential conditions that may influence the development of a protective weathering steel patina. Finally, a pilot program for washing weathering steel bridges, and washing intervals, is proposed.

LITERATURE REVIEW

Performance of Weathering Steel Bridges

Many of the early studies performed on weathering steel bridges concentrated on the performance of existing bridges in order to correlate their performance to factors such as exposure and environment. This research is presented in reports prepared by AISI, the Michigan Department of Transportation (MDOT), NCHRP, as well as several others. Subsequent research confirmed many of the observations and findings of the early studies. A list of documents examined as part of the literature review is included in Appendix A.

Patina Formation

The performance of weathering steel depends on the proper formation of a dense layer of corrosion product, or patina, to protect the steel from further atmospheric corrosion. Initially, the corrosion rate of weathering steel is similar to that of plain carbon steel; however, wetting and drying cycles, or natural weathering, causes weathering steel to develop a dense oxide layer on the exposed surfaces. This dense, well-adhered patina helps to slow additional rust formation and the corrosion rate stabilizes, as shown in Figure 2.

The development of the weathering steel patina may be hindered by environmental factors such as humid environments, extended periods of wetness, sheltering, exposure to deicing chlorides, and design details that permit water to pond on steel surfaces. In the mid-1980's, inspections performed by MDOT found bridges where the corrosion rate of the patina did not slow. At these bridges, the patina consisted of large flakes delaminating from the surface and/or exfoliating rust layers rather than a fine-grained, brownish-black oxide layer. The problems in Michigan appeared to correlate to heavy chloride exposure in urban or industrial areas, extended periods of wetness resulting from depressed or "tunnel-like" grade separations, and/or water contamination from deicing salts reaching the superstructure through leaking expansion joints, cracks in the concrete deck, or directly over the edge of the deck.

In most cases, early examples of poor weathering steel performance could be linked to two primary factors: heavy exposure to deicing salts and extended periods of wetness. Both of these factors are often present below leaking expansion joints or cracks in the concrete deck. In addition, traffic below bridge structures creates a "spray" or "fogging" that results in chlorides being deposited on the bridge structure from below. In this "splash zone" the chlorides often settle onto the top surface of the bottom flange along with dust, dirt, rust flakes, bird droppings, and other debris. Past research commonly referred to this contaminant layer as a "poultice" that retains moisture and keeps chlorides in close contact with these horizontal surfaces. Poultice corrosion was a common observation on horizontal surfaces above traffic or in areas where water and dirt could migrate and settle outside of the splash zone.

It should be noted that mill scale on weathering steel does not have any significant effect on its overall performance. Mill scale does, however, create variation in the surface appearance of the protective patina. The recommendation of the AISI task group is to leave the mill scale unless aesthetics is a consideration.

Weathering Steel Corrosion Product Phases

Research has shown that the durability and protective qualities of the weathering steel patina depend on its chemical composition and structure. The corrosion products present on weathering steel structures typically contain many different phases, which result from the interaction of the steel and the environment. In general, amorphous corrosion products are considered to be protective and crystalline products are not as protective or durable. The corrosion product on weathering steel structures may contain goethite (α-FeOOH), akagenite (β-FeOOH), lepidocrocite (γ-FeOOH), magnetite (Fe_3O_4), hematite (Fe_2O_3), maghemite (γ-Fe_2O_3), and others. Each corrosion product phase has been correlated to a greater or lesser degree of corrosion protection. Goethite, particularly nanocrystalline and/or chromium-containing goethite, is considered particularly protective. Akagenite, lepidocrocite, maghemite and magnetite are considered less protective. Akagenite can readily harbor chloride ions within its crystal structure and has been found to be present in greater quantities in corrosion products of weathering steel in high chloride environments.

Corrosion Rate

As discussed above, and as shown in Figure 2, the corrosion rate slows and stabilizes as the protective patina is formed over the life of well-performing weathering steel. After the development of the protective patina, the corrosion rate of weathering steel was measured to be approximately four times less than that of plain carbon steel without copper. Extended periods of wetness and/or heavy exposure to deicing salts will prevent the formation of a dense patina on the weathering steel and the initial corrosion rate will continue, similar to that of plain carbon steel. Because the corrosion rate, or oxidation, of weathering steel is greatest at the beginning of its life, the environment and chloride exposure at the time the structure is put into service has a significant impact on patina performance over the remainder of the service life.

The study of Michigan bridges in the 1980's found weathering steel bridges were performing well if the steady-state corrosion rates were between 0.2 and 0.6 mils/year. Ideally, the corrosion rate will remain below 0.2 mils/year. Research performed in other countries, including the United Kingdom, confirmed this desired corrosion rate. The currently accepted steady-state corrosion rate was initially presented in NCHRP Report 314, which recommends a rate of 0.3 mils/year as an acceptable upper limit for patina development and pit growth. Due to the higher initial corrosion rate, section loss on the order of 10 mils (0.01 inches) could be expected as the patina develops, but this level of section loss is generally negligible when considering structural performance.

Selected Examples of Weathering Steel Bridge Performance

AISI performed a follow-up study in the early 1990's revisiting the original 49 bridges surveyed during the initial research. The intent was to evaluate the performance of these bridges after thirteen more years in service. Additional bridges were inspected as part of this work, including four weathering steel bridges in Iowa. The four weathering steel bridges in Iowa were inspected by Mr. Bruce Brakke of the Iowa Department of Transportation and Mr. Robert Nickerson, who was retained by AISI. The bridges were inspected from the ground and the slope walls adjacent to the abutments, so visual observations were not performed on the top side of horizontal surfaces over traffic. These inspections revealed:

- There was a noticeable difference between the exposed fascia girder and the sheltered interior elements. Exposed surfaces appeared to develop the patina rapidly and had small rust flakes. The interior surfaces also appeared to have a dense patina, but the rust flakes were much larger.
- When debris was allowed to build up, corrosion could occur if the debris was allowed to remain wet.
- A transverse drip groove on the underside of the concrete deck at the joints appeared to help keep water away from the girder ends.
- Overall, the bridges in Iowa were performing in "textbook" fashion; however, some bridges exhibited some micro-environment concerns.

- The primary cause of observed corrosion deterioration was inadequate deck drainage through the joints and scuppers.
- A white appearance was noted on the girder bottom flanges of the US30 Bridge in Ames and the I-35 Bridge in Wright County. It should be noted that these two bridges were visited by WJE engineers as part of this project.

The AISI report issued in 1993 reiterated and confirmed much of the research performed in the 1980's with regard to location selection and design details to achieve satisfactory performance of weathering steel structures. It was also noted that bridges constructed in accordance with the 1989 FHWA Technical Advisory were generally performing adequately. Several examples were given where bridges were constructed with heavy traffic and salting on the bridge deck, but the weathering steel was not exposed to traffic and salt spray from below. With the exception of leaking joints and drains, these weathering steel girders were performing in "textbook" fashion.

However, one particular example stood out in the 1993 AISI report. Structures S34-82123 and S35-82123 in Michigan were constructed (in 1972) in an urban area over heavy traffic and are exposed to heavy salt use from above and below. During the initial AISI inspection in 1981, the lower sheltered surfaces of the bridge were experiencing flaky/laminar rust, but it had not yet resulted in any measurable section loss. When the bridge was revisited in 1994 after being in service for 22 years, severe corrosion was observed over essentially the entire length of the bridge. Painting the corroded weathering steel was recommended. This example will be discussed again later in this report.

Recommendations for Use

Once the early research that evaluated weathering steel performance was complete, recommendations were developed for the proper design and use of weathering steel structures. Most notably, these guidelines are presented in the 1989 FHWA Technical advisory and NCHRP Report 314, also issued in 1989. Considerations for utilizing weathering steel often include economics (lower cost due to maintenance of paint coatings), safety (eliminating painting over traffic), and aesthetics. However, in all cases a weathering steel structure is only cost effective if it is used in the proper environment. The reports listed above, and many others, typically group the different environments into four categories: rural, urban, industrial, and marine (in approximate order of least aggressive to most aggressive). Due to increasing Environmental Protection Agency (EPA) restrictions, levels of atmospheric pollutants have been decreasing since the research of the early 1980's. As a result, it is expected that nearly all bridge structures in Iowa are located environments that may be categorized as rural or urban.

Microclimates present within each environment also affect the performance of weathering steel bridges. For example, a weathering steel structure in a marine environment could perform very well or a structure in rural environment could perform poorly due to varying microclimatic conditions. Conditions can also vary from location to location on the same bridge superstructure. Some factors commonly affecting microclimates include:

- Shelter
- Orientation
- Angle of exposure
- Time of wetness
- Chloride exposure
- Atmospheric pollutants

- Debris
- Continuous moisture and thermal effects
- Structural details and geometries

Recent studies performed by the Illinois Department of Transportation (IDOT) found that significant microclimates can be formed by the spray from moving traffic. The tires of moving vehicles spray water and salts into the air creating road salt mists in the vicinity of the roadways. In addition, the moving vehicles create turbulence in the air that can force air vertically, splashing it onto bridge girders. The road salt mists and splash zone areas are affected by traffic volumes, traffic speeds, and the percentage of trucks. The research by IDOT found that salt spray can be found over one mile downwind of major highways, but in most locations the salt accumulation tapers out within six tenths of a mile from the highway. Road salts were found to be applied approximately 17 times per year on average in Illinois, causing bridge sites within 100 meters of busy roadways to have salt accumulations comparable to moderate-to-severe coastal regions. Therefore, bridge spans over roadways are likely to have high rates of chloride deposition, but the spans away from the roadway, near the abutments, are by no means immune from chloride contamination. The 1989 FHWA Technical Advisory states, based on information available at the time, that weathering steel structures can be used successfully in the United States at chloride deposition rates up to 0.5 mg/100 cm^2/day, average for structures with bold exposures (fully exposed to sun and weather). The acceptable deposition rates would be lower for structures in sheltered areas or areas subjected to extended periods of wetness. Chloride deposition rates and time of wetness can be evaluated using ASTM Test G92 *Characterization of Atmospheric Test Sites* and ASTM Test G84 *Time of Wetness Determination*, respectively.

When both environments and microclimates are considered, weathering steel structures will perform best under the following conditions:

- Site selection avoids polluted industrial environments, marine/coastal environments, and areas with high humidity/rainfall.
- Atmospheric exposure creates sufficient wet/dry cycles without extended periods of wetness.
- Exposure to heavy concentrations of corrosive pollutants, especially chlorides, is avoided.
- Washing of the steel surfaces occurs due to bold exposures (fully exposed to sun and weather).
- Proper design detailing that diverts runoff water and avoids ponding moisture, dirt, and/or debris.

Besides rainfall, moisture can be generated from many sources, including condensation, runoff through leaking joints or cracks in the concrete deck, traffic spray, and fog. Unfortunately, while these sources of moisture wet the steel surfaces, they do not serve as reliable mechanisms to wash contaminants away. In addition, water resting on horizontal surfaces such as the top of a girder bottom flange has been observed to affect the lower portions of the girder web due to capillary action through the weathering steel patina. Furthermore, rain events will wash contaminants away from the steel surfaces, but this benefit is typically limited to the exterior face of the fascia girders. Consequently, design recommendations focus on details to reduce standing water on steel surfaces, including:

- Reducing or eliminating joints
- Sloping horizontal surfaces
- Avoiding reentrant corners
- Sealing box sections
- Detailing diversion plates or weeps for easy discharge of water

Inspection of Weathering Steel Bridges

Remediating areas of advanced corrosion on a weathering steel bridge superstructure where a protective patina has not formed is often costly and negates the anticipated cost savings for this type of superstructure. Therefore, proper inspection of a weathering steel superstructure is essential for determining the overall performance of the patina and identifying problem areas early so they can be addressed before deterioration progresses.

Good patina performance is typically indicated by a fine grained, dark brownish-black, tightly adhered, stable rust layer on the surface of the weathering steel. The protective oxide layer depends on the formation of an initial amorphous layer of corrosion product. The introduction of salts and extended periods of wetness causes other types of corrosion product to form, such as less protective crystalline forms. While the difference between a good patina and a poor patina is determined at a microscopic level involving types of corrosion product and chloride content, early research correlated patina development and performance to various visual indicators. For example, the formation of less protective crystalline oxides resulted in the formation of loose rust scale on the patina surface. Furthermore, it was found that rust scale appearance is proportional to chloride content. Weathering steel surfaces with higher concentrations of chloride in the oxide layer were found to have developed larger, thicker rust flakes in the patina.

Ultrasonic thickness gages have been used to measure the depth of corrosion penetration. If the depth of penetration is known, the approximate corrosion rate can be estimated from the age of the structure to assess if the corrosion rate has stabilized. The literature indicates that this testing technique has been used with varying degrees of success. Even with trained equipment operators, the potential exists for variations in the measured thicknesses and/or uncertainties in the results. Also, the initial thickness of the steel plate is typically not known due to fabrication tolerances. Based on these factors, the use of ultrasonic thickness gages for this project was not pursued.

NCHRP Report 314 presents guidelines to evaluate the condition of the oxide layer on weathering steel structures. Particularly, the color and texture of the oxide layer can be used to evaluate if the patina is protective or not. However, it also suggests that visual observations alone can be misleading and recommends hammer tapping or wire brushing to determine if the layer is adherent or debonds in the form of granules, flakes, or laminar sheets. The inspector should be familiar with the appearance of weathering steel patinas that form in various environments and microclimates. For instance, the exterior face of a fascia girder may develop a dark-brown, tightly-adhered patina, but the interior face of the same girder may have a dark-brown color with non-adherent, coarse rust flakes. The NCHRP report presents characteristic colors and textures for weathering steel oxide layers, and these appearance guidelines are summarized in Tables 1 and 2.

Table 1. NCHRP 314 Appearance Guidelines for Color of the Oxide Layer

Color	Condition
Yellow orange	Initial stage of exposure
Light brown	Early stage of exposure
Chocolate brown to purple brown	Development of protective oxide
Black	Nonprotective oxide

Table 2. NCHRP 314 Appearance Guidelines for Texture of the Oxide Layer

Texture	Condition
Tightly adherent, capable of withstanding hammering or vigorous wire brushing	Protective oxide
Dusty	Early stages of exposure; should change after a few years
Granular	Possible indication of problem depending on length of exposure and location of structure
Small flakes, 6mm in diameter	Initial indication of nonprotective oxide
Large flakes, 12mm in diameter or greater	Nonprotective oxide
Laminar sheets or nodules	Nonprotective oxide, severe corrosion

More recent research conducted in Japan developed a similar scale for evaluating the color and texture of a weathering steel patina. This approach is similar to the guidelines presented in NCHRP Report 314 except that an appearance index between 1 and 5 is used describe the condition of the oxide layer, as shown in Table 3. In general, an appearance index rating of 4 or 3 represents protective, durable rust where the corrosion rate has stabilized. When the index rating progresses from 3 to 2 or 1, the corrosion rate of the underlying steel exceeds the weathering corrosion rate and nonprotective thick rust is forming. This correlation between the appearance index rating and the corrosion rate is shown schematically in Figure 3.

Table 3. Appearance Indices of the Oxide Layer[1]

Appearance Index Rating	Oxide Layer Thickness	Description	Rust Flake Size
1	> 800 μm	Large swelling and laminated flaky layer	> 25 mm
2	> 400 μm	Partial swelling and flaky layer	5 to 25 mm
3	< 400 μm	Non-uniform rust	1 to 5 mm
4	< 400 μm	Adherent and uniform dark brown rust	Fine, < 1mm
5	< 200 μm	Light brown rust	Fine

The inspection techniques discussed above must be done at close range in order to accurately evaluate the color and texture of the oxide layer, as well as to identify variations in the condition. It was found that various State Departments of Transportation are beginning to adopt some form of patina evaluation and inspection techniques. The NYSDOT has developed inspection techniques based on the guidelines in NCHRP Report 314 to help inspectors evaluate the performance of the protective patina. It is our

[1] Hara, S., et al., "Taxonomy for protective ability of rust layer using its composition formed on weathering steel bridge," *Corrosion Science* 49 (2007), p.1131-1142.

understanding that a weathering steel superstructure is assigned a rating based on the overall condition and appearance of the protective patina. Presumably, these ratings are then used to prioritize structures in need of maintenance and/or rehabilitation measures.

Maintenance of Weathering Steel Bridges

After routine inspections are performed, areas where the protective patina is not performing as expected may be identified. Many of the potential problems related to weathering steel relate to extended periods of wetness caused by dirt and debris on the surfaces and/or contamination from chlorides caused by inadequate management of water. Highway bridge structures are known for collecting contaminants, such as chlorides, dirt, debris, bird nests, and other foreign matter, on horizontal surfaces. Therefore, weathering steel should not be perceived as a maintenance-free material. Often, the areas of excessive corrosion are easily remediated by addressing the source of the problem. The 1989 FHWA Technical Advisory and NCHRP Report 314 present routine maintenance items that may be necessary to address problem areas, including:

- Controlling roadway drainage by:
  - Diverting water away from low spots and horizontal surfaces
  - Cleaning troughs of joints
  - Resealing deck joints
  - Sealing leaking cracks in the deck
  - Maintaining scuppers
- Periodically removing dirt, debris, and other deposits that hold moisture by:
  - Hosing off the bridge
  - Scraping off loose sheets of rust
- Maintaining screens over access holes
- Removing vegetation that prevents drying
- Painting areas of excessive corrosion when necessary

Washing

Although bridge washing is a recommended maintenance action included in the FHWA Technical Advisory, there are two differing opinions regarding the effectiveness of washing. The research of the early 1980's suggested washing on a regular basis to remove chlorides before they are trapped by additional dirt, debris, and soot. The FHWA sponsored forum in 1988 discussed both sides of the washing debate. On one hand, many agencies considered washing as an effective method to remove chloride contaminants. On the other hand, it was stated that simple washing does not provide enough flow over a steel surface to remove salt contaminant build-up. In other words, salts will migrate to the interface between the oxide layer and the underlying steel, and washing is not able to significantly reduce these trapped chlorides.

Evidence shows that frequent natural washing, such as regular rains on a fascia girder, will help keep the chloride levels low on weathering steel surfaces. Annual high-pressure washing of the interior surfaces will remove surface contaminants, but it will not be effective in removing the chlorides within or below the oxide layer. Similarly, multiple high-volume washings that may help to remove chlorides in the oxide layer are not cost-effective.

Although high-pressure washing is not very effective in removing chlorides embedded in the patina, an FHWA study in the mid 1990's found some evidence that periodic water washing may help to reduce the corrosion rate. At a minimum, the various studies agree that high-pressure washing will help to remove dirt, debris, loose rust flakes, and surface chloride contaminants that are often responsible for causing extended periods of wetness. This type of washing is also effective in removing much of the poultice layer of dirt and chlorides from horizontal steel surfaces, which often produces a sponge-like condition that may hinder the development of a protective patina.

Painting

The weathering steel research performed since the early 1980's identifies painting as an effective remedial measure to address areas of excessive corrosion or protect areas where the patina has not formed. The literature review identified several studies related to proper surface preparation techniques to remove the chloride contaminants from the steel surfaces and pits. Limited research relating to rust-stabilizing treatments was also found; however, these treatments were often used as a sacrificial coating applied before the bridge is erected to help accelerate the development of the stable oxide layer. In some cases, rust-stabilizing treatments were applied to in-service bridges, but surface preparations similar to that required for painting were needed. The high cost of preparing and painting in-service bridges offsets the initial cost benefits of the weathering steel. Although painting can be an extremely effective remediation tool for poorly performing weathering steel, this type of remediation is beyond the focus of this report.

FIELD INVESTIGATION AND DISCUSSION

Investigation Approach

To maximize the efficiency and effectiveness of our field investigation, WJE experimented with various testing procedures, techniques, and documentation strategies in advance of the Iowa site visits. We also developed customized wireless information processing tools to record our field notes, test results, and photographs. Additionally, we conducted trial experiments to confirm the suitability of our proposed field testing procedures and explored their respective limitations. By evaluating and refining the proposed testing program prior to arriving on-site, we ensured maximum consistency and quality of the information obtained from the selected sample structures in Iowa.

Field Investigation of Illinois Pedestrian Bridges

During the development of the testing approach, WJE performed field inspection and testing on several weathering steel bridge structures in the vicinity of our Northbrook, Illinois office. These structures all carried pedestrian and other non-motorized traffic, but varied considerably in detailing and environment. Accordingly, WJE was able to observe and test weathering steel with a wide range of performance conditions.

Various pedestrian bridges visited in Illinois exhibited poor patina performance, and these structures tended to be directly exposed to salt spray from roadway traffic below or to deicing salts used on the bridge deck above. It was also noted that the design details influenced the patina performance. For example, member and connection details that permitted debris and dirt build-up or trapped moisture on the steel tended to result in increased flaking and/or patina delamination in these areas. Similarly, regions of members exposed to salt spray from below but shielded from the benefits of natural rain washing and drying action performed poorly.

One pedestrian bridge carrying a walkway over a stream in a local park provided an extreme example of rapid weathering steel deterioration. Reportedly, this structure was approximately 10 months old at the time of our inspection and had been installed in December 2011 to replace, in-kind, a similar weathering steel pedestrian bridge that was experiencing severe corrosion-related deterioration and section loss. The wooden plank walkway of the new bridge structure allowed deicing salts to leak directly onto the truss bottom chord and floor beams. On these lower members, WJE observed notable deterioration of the protective oxide layer (Figure 4), with the initial stages of pitting and poor patina development. Conversely, the main truss top chords, web members, and railings all appeared to be still developing a patina without signs of distress (Figure 5). Observation of this structure reveals the potential effects of seasonal installation on the ability of weathering steel to initially develop its protective patina. Specifically, installations in the late fall or early winter of previously unexposed weathering steel may preclude effective patina development if exposed to significant chloride and moisture levels early in the life of the structure. This initial chloride contamination can lead to an accelerated corrosion rate and the inability of weathering steel to develop its protective oxide layer.

WJE also made notable observations during the inspection of a pedestrian bridge over the Des Plaines River located on an unpaved trail in a forest preserve. Figure 6 shows its general arrangement and environment. Though considerably older than the other local structures observed (aerial photographic records indicate the structure predates 1993), a combination of proper detailing and no salt exposure promoted excellent patina development and long-term performance of this truss bridge. A close-up photograph of a typical area of patina is shown in Figure 7.

During the inspection of the Illinois pedestrian bridge structures, WJE also established the effectiveness of a tape adhesion test to provide accurate and rapid confirmation of patina performance. On the well-developed patina of the pedestrian bridge over the Des Plaines River, a tape test was able to extract only a limited number of very small rust flakes. On structures with poorly-developed patinas, the tape test removed significant quantities of large, thick rust flakes. As a result, the tape adhesion tests appeared to provide a strong correlation between the size and spatial distribution of rust particles on the tape sample and visual observations of patina performance. Particularly for patinas performing well, other means of physically sampling the rust flakes presented disadvantages. Specifically for excellent patinas, scrapings were largely ineffective in providing meaningful information about the size or spatial distribution of the rust flakes. However, a tape test provided accurate assessment of both of these parameters by keeping the flakes intact and situated in their relative locations. In addition, the tape test provided information regarding the adherence of the protective oxide layer to the underlying weathering steel.

In general, the field work on Illinois pedestrian weathering steel structures provided WJE an opportunity to conduct the anticipated field tests on a trial basis in order to refine the testing techniques and data collection approach. Although each of the tests used in the Iowa site visits is described in detail in the following sections, some key observations made during our initial Illinois field testing include:

- Visual inspection of the structure is adequate to make overall assessments of the patina's condition and to identify problem spots or locations where detailed testing should be performed.
- Tape adhesion testing provides fast and accurate substantiation of visual observations of patina performance and yields useful information for virtually all patina conditions encountered. It also preserves this information on the tape sample and permits more detailed comparison to future performance at a later time, if properly stored.

- The patina condition index (described later) used for the Iowa field investigation is suitable to quantify visual inspections of the steel, and these results can be directly confirmed by tape testing using the same criteria.
- Chloride testing with CHLOR*TEST brand kits is limited to patina conditions where the surface can be adequately prepared to seal the sleeve to the weathering steel. The test would leak if used on unprepared surfaces or poorly performing patinas. Leakage of the test fluid may occur through pores and delaminations beneath the surface of the patina, even if an adequate seal is made.
- Scrape testing is a practical means to collect samples of larger rust flakes for subsequent laboratory testing but yields limited other useful information.

Laboratory Spray Testing

WJE also conducted spray testing on eight 1/2-inch thick weathering steel plates to observe how the early stages of patina development were influenced by the presence of salts. Although the plates had been previously exposed to ambient outdoor conditions during the summer of 2012, patina formation had hardly progressed at all at the time of spray test initiation due to extremely dry local weather during that period. The plates were then placed in an exposed location outside the WJE laboratory and repetitively sprayed to produce wetting and drying cycles. Four of the plates were sprayed with deionized water, and the remaining four plates were sprayed with a solution containing 15% sodium chloride by weight. WJE initiated the testing on October 15, 2012 and continued spraying intermittently through November 20, 2012 at the onset of freezing temperatures. We sprayed the plates only when they were initially dry; in total, WJE applied 16 wetting and drying cycles to the plates. In between spray applications, the plates also experienced natural wetting and drying due to occasional rain showers and dew formation. As discussed in the literature review section above, this number of salt-spray cycles is approximately equivalent to one winter season in Illinois.

WJE photographed the plates before initiating testing on October 15, 2012 and again on December 7, 2012. In general, the plates exposed only to natural moisture and deionized water showed minor advancement in patina development, but the rust forming on the steel surface did appear to be consistent with good patina performance. In contrast, the heavily salted plates began to exhibit reddish, streaky surface rust formation after only a few spray cycles. This rust progressed more aggressively despite intermittent natural washing by rain and showed beginning signs of distress. At the time of final photographs, 17 days had passed since the last spray application, with several natural wetting cycles in the interim. Figure 8 shows representative conditions of the plates before and after testing.

The deleterious effects of chloride contamination on the early stages of patina formation are clearly evident from the results of this short-term spray study. WJE will continue to allow these plate specimens to weather naturally in our laboratory yard and periodically monitor their performance. Additional spray or other laboratory tests may be performed on the plates at a later date, once the patinas have had an opportunity to mature.

Field Investigation of Iowa Bridges

Prior to conducting the field investigation of Iowa bridges, the Iowa DOT provided an inventory of weathering steel bridges in the State. WJE reviewed this inventory to evaluate the various environments (rural, urban, etc.) to which the weathering steel bridge structures were exposed. It should be noted that a suburban environment was also included for the purposes of the Iowa investigation. The review categories included the age of the structure, National Bridge Inventory (NBI) superstructure rating, and potential micro-climate factors such as traffic counts above, traffic counts below (if any), span lengths, clearance below, and other geometric/layout factors that could be determined from satellite images.

In total, thirty-one separately identified structures were selected for the Iowa field investigation. These structures were grouped into various location environments, identified as Field Selection Number. In some cases, such as side-by-side structures or multiple bridges along the same stretch of roadway, structures were assigned the same Field Selection Number. A map of the different field inspection locations is shown in Figure 9 and the list of structures is shown in Table 4 below. In addition, maps and more detailed information for the various structures are provided in Appendices B and C.

Table 4. List of Bridges Selected for the Iowa Field Investigation

Field Selection No.	Structure Name	Bridge ID	County	Year Built
1*	EB IA-930 over US-30	0819.6R930	Boone	1972
2	US-151 over IA-36	3175.5R151	Dubuque	2002
		3175.5L151	Dubuque	2002
	US-151 over the N. Fork Maquoketa River	3175.6R151	Dubuque	2002
		3175.6L151	Dubuque	2002
3	US-30 over IA-14	6485.3R030	Marshall	1995
		6485.3L030	Marshall	1995
4	US-65 over Avon Road	7774.0R065	Polk	1997
		7774.0L065	Polk	1997
5	I-35 and I-80 over IA-28	7731.5R080	Polk	1999
		7731.5L080	Polk	1999
6	Douglas Avenue over I-35 and I-80	7726.1O080	Polk	2002
7	E. 14th Street (US-69) over I-235	7785.5S069	Polk	2003
	E. 12th Street over I-235	7709.1O235	Polk	2002
	E. 9th Street over I-235	7709.0O235	Polk	2001
	Pennsylvania Avenue over I-235	7708.9O235	Polk	2002
	E. 6th Street over I-235	7708.8O235	Polk	2002
	I-235 over the Des Moines River and the	7708.5S235	Polk	2007
	I-235 E.B. Entrance Ramp at 2nd Avenue	7708.5A235	Polk	2003
	2nd Avenue over I-235	7708.3O235	Polk	2003
	2nd Avenue Ramp over I-235	7708.3A235	Polk	2002
	3rd Street over I-235	7708.2O235	Polk	2003
	5th Avenue over I-235	7708.1O235	Polk	2003
	6th Avenue over I-235	7708.0O235	Polk	2004
	7th Street over I-235	7707.9O235	Polk	2003
8	I-80EB and I-29SB over Indian Creek	7802.4R080	Pottawattamie	**
9	US-218 over IA-22	9280.9R218	Washington	1995
10	US-75 over Bus-75 and Railroad	9799.5R075	Woodbury	1999
		9799.5L075	Woodbury	1999
11	FM RD A-34 over I-35	9811.3O035	Worth	1970
12*	FM R-75 over I-35	9951.4O035	Wright	1971

*Included in the AISI study during the early 1990's

**Bridge constructed with painted steel in 1968 and widened with weathering steel at later time, date unknown.

Three of the thirty-one structures were constructed between 1970 and 1972, and two of these three structures were included in the AISI research in the early 1990's. The remaining twenty-eight structures were constructed between 1995 and 2007. Four of these structures are over rivers and are not exposed to any significant salt spray from below. Finally, the NBI superstructure rating for these bridges ranged from *9—Excellent Condition* to *5—Fair Condition*. The Iowa field investigation was performed in November 2012.

Assessment of Inspection and Testing Methods

The following sections describe the various inspection techniques utilized by WJE during the Iowa field investigation, including visual inspection, tape adhesion testing, chloride testing, color testing, and physical sampling. For each inspection/testing method, the procedure is presented along with advantages, disadvantages, practicality, and repeatability. A discussion summarizing the results and findings is also provided for each inspection/testing method. An inspection summary form for each Iowa bridge structure is included in Appendix C, and each form includes information related to the bridge environment, location, age, traffic counts, structure description, summary of condition, and testing performed, as well as several photographs obtained during the field inspection.

Visual Inspection

WJE subjected all of the sample bridges in Iowa to visual inspection and evaluated each structure according to a patina performance index adapted from previous research[2]. Table 3 above summarizes the assessment criteria and corresponding categories of the patina performance index rating system. This index was selected as a visual observation reference because it provides a quantitative means to assess patina performance based on the size of the rust flakes comprising the patina, as well as its surface texture and coloration. These evaluation criteria and the detailed characteristics of each of the five patina classifications are discussed in more detail below.

In general, it was found that the bridges constructed in Iowa since the mid-1990's are in conformance with the recommendations provided in the 1989 FHWA Technical Advisory. As a result, the bridges have been detailed to avoid many of the locations where water can pond and result in extended periods of wetness. As a result of these design details, many of the causes of premature deterioration in early weathering steel structures have been eliminated in these newer Iowa bridge structures. These design considerations include:

- Narrow flange widths, (Figure 10).
- Narrow splice plates to prevent ponding water at the leading edge, (Figure 11).
- Coped stiffeners that do not trap water, (Figure 12).
- Minimal use of transverse and longitudinal stiffeners, (Figure 10).
- Water diverter plates installed on bottom flanges, (Figure 13).
- Elimination of joints by use of integral abutments, (Figures 13 and 14).
- Painting end of steel members below joints even in integral abutments, (Figures 13 through 15).
- Minimal use of scuppers.
- Elimination of bottom flange lateral bracing, even on curved girders, (Figure 10).

[2] Hara, S., et al., "Taxonomy for protective ability of rust layer using its composition formed on weathering steel bridge," *Corrosion Science* 49 (2007), p.1131-1142.

Visual Inspection Procedures. The visual inspection of weathering steel focused on specific characteristics of the appearance in order to consistently rank the condition of the patina using the selected visual performance index. WJE first noted the color of the patina in the region being considered. The overall shade and tone of the color as well as the uniformity of the coloration (or lack thereof) were of interest when rating the patina. Once color was observed, WJE moved closer to the region in question to visually assess the texture, size, and spatial distribution of the rust products. The adherence and approximate size of any rust flakes on the patina surface are key parameters in consistently ranking the patina. A small scale held against the region of patina being considered proved helpful in quickly estimating average flake size. Whenever possible, WJE inspectors tried to be within arm's length of the patina to gauge its adherence, texture, and flakiness.

WJE visually rated the patinas in terms of both overall and localized performance. To ensure consistent rating of patina performance from bridge to bridge, WJE typically observed the corrosion products up close using an aerial lift or by closely approaching areas near the abutment slope walls. Once close-up observations of patina performance were made, WJE was able to extend ratings to other portions of the bridge observed at greater distances by visual comparison. Overall rankings indicate performance of a bridge structure on average; localized rankings help in quantifying the performance of the weathering steel at trouble spots and in identifying the range of conditions present on a given bridge.

At times, WJE elected to further differentiate patina performance beyond the basic performance index by using half-point scoring. In other words, visual observations or other tests sometimes indicated that patina performance fell between two of the five primary category indices. In such situations, WJE used a half-point adjustment to more precisely indicate the condition of the patina. Based on our Iowa field experience, we feel that such a differentiation is feasible and is helpful in distinguishing between a patina that is solidly within a ranking index category and one that is trending toward the next category. However, we feel that more precise (e.g., quarter-point) ranking of patina performance adds little useful information for quantitative comparison to other regions or structures and may be difficult to consistently implement. Visual inspection and ranking of patinas can be done without any more detailed testing. However, with the exception a small portion of the structures included in the field investigation, WJE typically supplemented visual assessment with tape testing, at a minimum.

WJE observed significant bridge features during the course of visual inspection and rating of the patina. These items were occasionally noted during the inspection and often helped to reveal information related to the performance of the patina in each structure. Many of these are either causal to or symptomatic of the condition of the patina, and include:

- Bridge geometry, location, traffic exposure and general structural detailing
- Drainage detailing and substructure rust staining
- Bridge slope and distribution of chalky poultice corrosion of horizontal elements
- Failure of expansion joints, deck cracking, or other means of water infiltration
- Integral versus conventional abutment construction
- Paint at ends and joints
- Proximity of any adjacent bridge structures

Evaluation of Visual Inspection Methods. Visual inspection of weathering steel is highly effective for making an overall assessment of patina performance and trouble-shooting problem areas. It is a fast process, and was often found to be adequate to describe conditions on the bridge independent of other testing. WJE found that after inspecting several bridges exhibiting a range of patina conditions, we were often able to confidently assign patina index ratings based on a visual survey alone.

WJE also found that, even with two inspectors working independently on the same structure, there was consistency in visual ratings after working together on only a few bridges. This suggests that consistency in visual inspections is achievable in the context of a larger field inspection/inventory program, even with multiple inspectors, provided some basic training is given.

The patina rating index is a useful tool in several contexts. In addition to providing a consistent quantitative description of the overall performance of a weathering steel bridge, it identifies the range of conditions present. This type of rating also facilitates comparison of trends in weathering steel behavior across multiple bridges or over multiple inspection periods. Use of a well-defined ranking system can be made more effective by including a description and comparison of the effects of influential parameters (e.g., bridge location, geometry, traffic conditions and salt exposure, etc.).

Though visual inspection is an excellent means of evaluating Iowa weathering steel bridges, WJE believes more detailed testing is also necessary to facilitate consistency in an inspection program. Other supplemental testing is beneficial to the bridge evaluation process because it provides confirmatory evidence to supplement the visual inspection findings.

Visual Inspection Summary. The patina rating index used during the field investigation is comprised of five categories that represent different stages of performance. Index rating Category 5 typically indicates an immature or developing patina and the remaining categories indicate a gradient of performance ranging from good protective behavior (Category 4) to substantial failure of the patina and section loss (Category 1). WJE observed the entire range of patina conditions during our site visits in Illinois and Iowa; however, a vast majority of the bridges inspected in Iowa ranged between Category 4 and 2. Visual inspection results for each of the Iowa bridge structures are summarized in Appendix C.

Occasionally a Category 5 patina condition was observed on the Iowa bridges, but this was typically in isolated areas of members where there was visual evidence of some covering (e.g., spilled concrete, mill scale, etc.) and/or shielding of the weathering steel from normal exposure conditions that could delay the development of the patina. Category 5 patinas are typically well adhered, with a relatively smooth surface texture and very small rust particle size. However, they are often lighter and much more reddish in color than more advanced or mature patinas. Figure 16 is a close-up image of a Category 5 patina representative of the localized conditions WJE observed on the sample Iowa bridges.

Index Category 4 indicates excellent patina performance. Steel in this category has weathered as intended, with a tightly adherent patina composed of small rust particles forming an effective protective barrier against further corrosion of the underlying steel. The coloration of a Category 4 patina is typically a uniform dark brown when viewed at a moderate distance, although close inspection of the corrosion products reveals colors ranging from very dark brown to lighter brown, as shown in Figure 17. Occasionally, there may be hues of purple or isolated metallic spots. No matter the color, the pattern of coloration is most often uniform and has little variation. Also visible in Figure 17 is the relatively small size of the individual rust product clusters that are constituents of the patina. The patina surface may be somewhat rough but uniform, indicative of a thin, even, adherent layer. Little to no rust will be removed if scraped with a fingernail or hand tool. Particles that are removed are typically less than 1mm in diameter.

Index Category 3 patinas are still performing well in terms of forming the protective oxide layer, but they have slightly larger rust flakes on their surfaces. Some of these flakes may begin to loosen and provide pits and gaps where moisture and salts can be retained. Small, non-adherent flakes may be able to be removed with a fingernail or hand tool, and these flakes are typically 1 to 5mm in diameter. However, if these are removed, the remaining patina beneath appears adherent, dense, and relatively impervious. The coloration of a Category 3 patina is generally uniform and dark brown, but the pattern may begin to vary more as individual flake size increases. At transitions from a Category 4 to a Category 3 patina (e.g., near the bottom of a girder web), the brown color often darkens. Figure 18 illustrates a typical Category 3 patina.

Index Category 2 is representative of a patina that may not be functioning as a protective oxide layer. Typical conditions for ranking in this category consist of large, loose flakes covering the majority of the region. The patina is increasingly thicker and more permeable, with many crevices, pits, and small delaminations that allow moisture and salts to infiltrate the system. Pitting may begin to be of concern in members with Category 2 patinas. The color of Category 2 patinas is often non-uniform, as larger rust flakes result in blotchiness and reddish or black rusty discolorations, and salt stains become more frequent and noticeable. The size of the rust flakes typically ranges from 5 to 25mm in diameter. Figure 19 highlights many of these characteristics in a representative image of a Category 2 patina on the underside of a girder bottom flange.

Index Category 1 patina conditions were seldom observed during WJE's Iowa site visits. Category 1 patinas were found in isolated, localized areas and were usually attributable to a concentrated source of moisture and chloride contamination, such as leaking joints or girder top flanges beneath cracks in a heavily salted concrete deck. Figure 20 shows a Category 1 patina on a heavily chalked area on top of an interior girder bottom flange, a common problem area on some bridges. Characteristics of Category 1 include layered delamination of the patina (loose rust flakes typically greater than 25 mm in diameter) and possible section loss. The thickness of the rust increases substantially, and permeability and pitting in the adhered material permits salts and moisture to continue the corrosion process deep beneath the surface for longer periods of time after wettings. Category 1 patinas are non-uniform in color, and very large chunks and flakes of rust can frequently be removed by hand.

As mentioned previously, conditions other than the patina index rating were noted on the Iowa bridges. One of the most widespread and significant conditions observed was chalkiness of the tops of the interior girder bottom flanges. This phenomenon and the resulting corrosion are frequently referred to as poultice corrosion. Typically, bridges with any significant salt exposure displayed a poultice layer coating the top surfaces of the bottom flanges and other horizontal elements. The appearance of this layer was often mottled as shown in Figure 21.

WJE largely attributes this chalky layer to the natural deposition of salts and dirt from traffic spray below. Often the slope of the girders permits salts and fine particulates dissolved and suspended in spray water to migrate along much of the length of the girder, such as from areas directly over traffic to the girder ends near the abutments. This layer of salts, dirt, debris, and corrosion product results in extended periods of wetness due to trapped moisture, in turn causing additional poultice corrosion. In some cases, poultice corrosion was reduced or absent in regions of a bridge that did not see salt spray from below, where moisture drained away from the area, or was blocked by diversion plates. In many cases, the chalky layer could be largely removed by brushing with a hand or with a wire brush, confirming that it is not a part of the patina itself. However, the appearance of the patina did not easily fit into one of the patina index categories discussed above because the rust particles were typically larger but more widely dispersed. In some cases, severe deterioration of the patina (large, flaky delaminations) corresponded to heavy chalking, but in other cases, chalking was present without a significant effect on patina performance. The effect of poultice corrosion on patina performance is likely highly dependent on other variables influencing a given bridge.

Tape Adhesion Testing

WJE performed tape adhesion testing on the vast majority of the weathering steel bridges sampled in Iowa for this study. Tape testing was used to provide verification of visual patina index ratings, track patina performance on different surfaces within a structure, and allow more detailed comparison of rust flake size and density to other parameters such as chloride ion concentration. In addition, the tape test samples provided a permanent record of the non-adherent rust particle size and distribution for future reference after the field work was completed.

Tape Adhesion Test Procedures. Adhesion testing was performed in general accordance with ASTM D3359. To ensure consistency of the results, we used a white cross-hatch tape manufactured by the SEMicro Division of M.E.Taylor Engineering, Inc., specifically to replace the discontinued Permacell P-99 tape specified in the ASTM Standard. To conduct the tape adhesion test, a strip of tape approximately 8 to 12 inches long was pressed firmly onto the patina surface being studied. After waiting for a period of approximately one minute, the tape was peeled off of the surface quickly and smoothly at a steep angle (i.e., pulling the tape doubled back over itself rather than outward from the patina surface). Once removed, the tape specimen provided a record of the rust flake size and spatial distribution. WJE adhered the completed tape specimens to the inside of clear sample bags for future assessment. By storing the tape specimens inside sample bags, the rust flakes could be examined and measured without disturbing them. The tape samples were then used to assess the flake size and density and assign the patina an index category. For patinas in generally good condition, small flake sizes were accurately measured using a handheld 10x magnifying lens with a built-in measurement scale. The typical and largest rust flake sizes (excluding obvious outliers) in a given sample were measured to the nearest 0.5 mm and compared to the index rating criteria.

As a practical note, the specified time interval was occasionally extended or reduced, particularly if other tests were being simultaneously conducted. It was found that the time interval of tape adherence to the weathering steel made no noticeable difference in the test results. In addition, pulling the tape off at a steep angle on significantly deteriorated patinas would cause larger flakes to peel away from the tape itself or become damaged. In these cases, we adjusted the angle of pull to ensure the removed flakes remained intact and in position on the tape sample.

Evaluation of the Tape Adhesion Tests. The tape adhesion test is a relatively quick, low-cost, and very effective way to gather and preserve more detailed information about patina performance on a bridge. The most significant cost is obtaining arm’s length access to the weathering steel surface. As mentioned previously, the tape adhesion test provides more comprehensive information for assigning a patina index rating than visual inspection alone. This is primarily due to the ability to accurately measure flake size, which is more difficult to evaluate visually when the flakes are still adhered to the patina surface, particularly for patinas in moderately good condition (i.e., Category 2.5 to 4.0). The density of flakes removed by the tape also provides more detailed information about the overall adherence of the patina than visual inspection alone, and preserves the spatial distribution and size of flakes for consideration in a way that scrape tests do not.

Tape testing proved to be effective in a variety of conditions, most notably temperatures well below freezing. It also required no expensive or cumbersome equipment, requiring only a roll of tape, marker, sample bags, and a pair of scissors. The use of a handheld magnification scope (10x) with a built-in measuring scale was helpful in measuring the smaller rust flakes, but it may not be necessary for routine field testing.

The tape test provided consistently good performance on all patina surfaces encountered, from index Category 5 to Category 1, with one exception. A heavily chalked, or poultice, surface tends to inhibit adherence of the tape to the patina. This results in a tape test specimen that holds fewer, smaller rust flakes and more salts and dirt than a sample taken from a comparable patina without chalking. Figure 22 highlights the difference between a tape test on a typical patina and one taken over poultice corrosion. In the latter case, care must be taken to distinguish between salt and dirt deposits and actual rust particles when measuring flake size and assigning an index rating.

Tape Adhesion Testing Summary. While in Iowa, WJE recorded tape test results for patina conditions ranging from index Category 5 to Category 1. The specific test results for each bridge studied are summarized in Appendix C. Figures 23 to 27 provide representative examples of tape tests for all patina index rating categories. Surface areas with tape test flake size and density (an indication of overall patina adherence) corresponding to the stated patina index criteria strongly match the appearance of the sample photos for each category depicted in Figures 23 to 27.

Of particular interest are tape tests conducted on several of the girders to record patina variability from structural element to element on a given bridge. When multiple tape tests were conducted on a given bridge, WJE was able to identify trends in patina performance from one area of the bridge to another. An excellent example of this was the four tape tests performed on Structure 9811.3O035 which carries Farm Road A34 over rural Interstate 35 (Field Selection 11). Together, these tape profiles assess how patinas performed over the 40 year bridge service life by comparing results from exterior fascia surfaces to interior surfaces in locations both directly above traffic and away from traffic near the abutments. The index ratings for the girders of this bridge ranged from Category 4 to Category 1. The exposed, exterior surfaces of the fascia girders performed considerably better than the interior surfaces, showing little to no deterioration in the protective oxide layer after 40 years of service (typically rated as Category 4 to 3.5). The interior girder surfaces exhibited considerably more rust flaking, particularly at the bottoms of the girders (i.e., the bottom of the web and bottom flange, and especially the top of the bottom flanges, where significant poultice corrosion was present). The deterioration recorded by the tape tests over traffic was also markedly worse than that near the abutments. The tape tests directly over traffic rated about half an index point worse on surfaces generally performing well, such as the exterior of the fascia and above mid-height of the interior webs. However, at areas more prone to patina deterioration, such as the top of the bottom flange, the index rating over traffic was up to 1.5 rating points lower than the rating near the abutment.

Also of interest are tape tests of a fascia girder from an eastbound on-ramp adjacent to the I-235 Bridge over the Des Moines River, Structure 7708.5A235. The ramp crosses a minor access road parallel to the riverfront. The tape adhesion tests performed on the ramp fascia girder adjacent to the I-235 mainline structure suggest that heavy salt spray from the adjacent interstate caused significant deterioration of the exterior face of the fascia web and bottom flange. The middle portion of the exterior web fared reasonably well with an index of 3, but the patina was increasingly distressed as we examined lower on the girder, as shown in Figure 28. The bottom of the web, top of the bottom flange, and bottom of the bottom flange rated at indices of 2.5, 2, and 1.5, respectively. This corrosion is concerning given that records indicate this ramp structure was constructed in 2003; however, the damage was limited to a relatively short portion of the bridge where chloride-contaminated snow from plows on the I-235 mainline is deposited onto the ramp fascia girder. At other locations along the girder, the curvature of the ramp brought the exposed fascia surface out of range of direct snow or close enough to the mainline structure that the concrete deck shielded the girder from direct snow, as shown in Figure 29. The interior faces of the fascia girder were in considerably better condition, with an index rating of 3.5. Though some poultice corrosion was present on the interior bottom flange, the patina was adherent and showed no signs of flaking. This may be an indication that the interior surfaces of the ramp have a relatively short time of wetness each year since they see little moisture from the low-speed, minor traffic below.

The conditions noted on this ramp structure are in sharp contrast to trends typically observed, where the interior surfaces perform comparatively worse than the outside of the fascia. The combination of heavy, direct salt exposure from the adjacent structure and the lack of any significant traffic on the river access road below likely caused this exception to the patterns observed on other sample bridges. Similar conditions to those described above were also observed during our visit to Field Selection 8 in Council Bluffs. The exterior faces of the north fascia girder of Structure 7802.4R080 carrying eastbound I-80 over Indian Creek likely saw heavy direct salt deposition from westbound snow plows due to the proximity of the neighboring bridge (clear distance of approximately 19 feet). At the remaining locations of side-by-side bridges inspected, the clear separation between the bridges was approximately 35 feet or more. As a result, the snow thrown by snow plows from one bridge structure did not have a noticeable influence on the condition of the fascia girder of the adjacent structure.

Chloride Testing

WJE conducted tests to determine the concentration of chloride ions on the majority of the bridges in this study, including bridges in both Iowa and Illinois. The primary field chloride test utilized in this study was CHLOR*TEST, manufactured by CHLOR*RID International, Inc. After considering other commercially available chloride field tests, including the Bresle Test Kit manufactured by Paint Test Equipment, the Soluble Salt Meter manufactured by ARP Instruments, Inc., and the SaltSmart Sensor manufactured by Louisville Solutions Incorporated, we selected CHLOR*TEST for its simplicity, relatively low cost, flexibility in testing time, and ability to seal and adhere to the weathering steel substrate. The primary goal of chloride testing was to correlate chloride ion concentrations measured on weathering steel surfaces in the field with observed performance of the patina. WJE also performed chloride testing to measure the effects of bridge washing techniques on chloride concentrations. Additionally, by conducting chloride tests on adjacent areas of patina with similar surface and exposure conditions, we assessed the variation in chloride extraction with exposure time.

Chloride Test Procedures. CHLOR*TEST procedures are outlined in the manufacturer’s documentation, and WJE generally followed these procedures with the exception of testing time. Our field procedure typically consisted of the following:

- Select the test location and prepare the surface to which the sleeve will adhere.
- Empty the extraction solution into the latex test sleeve.
- Peel the backing off of the adhesive foam at the mouth of the sleeve.
- Without spilling the solution, partially adhere the sleeve to the weathering steel surface.
- Remove excess air from the sleeve, then firmly and completely seal the mouth of the sleeve to the weathering steel.

- Orient the sleeve such that the extraction solution is in constant contact with the steel surface, and massage the sleeve against the steel to circulate the solution and work it into the pits and voids of the patina. It is acceptable if loose rust flakes fall into the solution.
- Keep the solution in contact with the steel for 15 minutes, massaging occasionally.
- Once the extraction time is complete, carefully remove and hang support the sleeve upright.
- Using the provided steel tool, snap both ends off of the glass titration tube and place it into the solution, arrow pointing up.
- Place the included rubber dropper head over the top of the glass tube and squeeze once to initiate the flow of extraction solution through the titration tube.
- The test is complete when the solution has percolated through the top of the tube's fill to the cotton plug; the top layer of fill will appear bright yellow and typically stain the cotton.

The test results are indicated by the change in coloration of the fill in the titration tube. The chloride ion concentration in parts per million (ppm) is read directly from the scale printed on the tube. The reading is taken where the titration tube fill changes from white to pink. A sample extracting untraceable levels of chloride ions will not display any white in the tube. The precision of the measurement decreases with increasing concentration due to the variability of the scale on the titration tube. At the low end of the scale, results can be reasonably read to the nearest 1-2 ppm, depending on the clarity and sharpness of the color change in the fill. At higher concentrations, the precision of measurement may be closer to 3-5 ppm. Readings at all concentrations reportedly have no inherent bias. Note that on a theoretically solid, smooth surface, the CHLOR*TEST results in ppm would also correspond to an equivalent reading of micrograms per square centimeter if chlorides were extracted from the surface with 100% efficiency. Actual chloride extraction rates experienced by WJE in the field on weathering steel surfaces were much lower (typically 10% or less), as determined by subsequent laboratory chloride tests.

During the course of testing, it was determined that careful pre-test surface preparation is essential to the successful adherence of the CHLOR*TEST sleeve to the weathering steel substrate. Accordingly, the time and equipment needed to execute each test is increased beyond that outlined in the CHLOR*TEST product literature. Typically, WJE used a wire brush to clean the surface to which the CHLOR*TEST sleeve was adhered. A circular metal stencil, approximately equal in size to the inner diameter of the CHLOR*TEST sleeve, was used to protect the test area from wire brushing that might affect the chloride extraction rate. Once the loose rust flakes and dirt were scrubbed off, tape was used to remove the remaining rust particles and dirt from the test perimeter. Figures 30 and 31 generally illustrate the extraction and titration tube stages of the CHLOR*TEST procedure, respectively.

CHLOR*TEST is capable of measuring concentrations of chloride ion below 60 ppm, which is the upper limit of the titration tube. Higher concentrations could be verified with QuanTab test strips, produced by Hach Company, Inc., and designed to measure higher chloride ion concentrations. The two measurement tools generally showed good agreement at locations where chloride concentrations would register on both devices. Lower levels of chloride ions measured by the CHLOR*TEST could not be independently verified in the field, but laboratory verification of CHLOR*TEST accuracy (and extraction efficiency) at low measured concentrations was performed on a limited number of core samples.

It should be noted that a series of chloride tests was performed in order to evaluate the extraction of the CHLOR*TEST solution as a function of time. The CHLOR*TEST time profile was performed on a small, uniform area of patina on an interior girder web near the east abutment of Structure 7731.5R080 of Field Selection 5, which carries Interstates 35 and 80 over Iowa Route 28. The tests were performed on the bottom of the girder web facing the interior of the bridge. A tape test made in this area indicated rust flake size varied from 0.5mm to 5mm, corresponding to a Category 3. As expected, WJE observed a relationship between CHLOR*TEST duration and chloride concentration measured; the results are illustrated in Figure 32. Although the chloride extraction increases with increased time, a 15 minute test time was selected for all chloride testing performed on weathering steel bridges in Iowa in order to provide consistent testing methods for possible future comparison of the results.

Evaluation of the Chloride Tests. During the Iowa field investigation, chloride concentrations from 0 ppm to well over 60 ppm were measured on weathering steel patinas. In general, the presence of measurable chloride ion concentrations was typically associated with some deterioration in patina performance; however, the extent of deterioration in terms of rust flake size and patina index did not always correlate closely with measured chloride concentration. We also found that vertical surfaces typically had lower chloride levels than adjacent horizontal surfaces. Heavy concentrations of chlorides were typically found on the tops of horizontal surfaces, particularly in areas with heavy poultice corrosion or where advanced flaking and delamination of the patina appeared to be allowing excess chlorides to be retained beneath the surface. Chloride test results for each sample bridge are summarized in Appendix C, as applicable.

Chloride testing was also performed beneath the patina layer on several bridges during the Iowa field investigation. At these locations, the patina layer was removed with a wire wheel grinder to essentially bare steel, as shown in Figure 33. These tests revealed chloride concentrations in the pits and on the surface of the base metal that were comparable to the chloride concentrations on the surface of the adjacent patina.

While the measurement of chlorides present in the CHLOR*TEST solution is likely accurate, laboratory testing revealed that the extraction efficiency of the test is typically very low (10% or less of the total water soluble chlorides) and may be heavily dependent on the surface condition of the patina itself. The patina layer has varying degrees of permeability; as corrosion-related deterioration progresses in the patina, this oxide layer becomes increasingly thick and porous. The permeability of the patina layer and the amount of chlorides deposited on the surface during patina development also contribute to the chloride levels within and/or below the patina layer. Based on the results of the chloride testing performed in the field and laboratory, it appears that the CHLOR*TEST is not able to withdraw and measure chlorides within or below the patina layer when practical extraction times are employed.

While the parameters and phenomena determining the rate of ingress of chloride ions from the surface of a weathering steel patina toward the base metal are complex and not have been completely studied, one simplified model that may be applied to the process is Fick’s Law of diffusion. In accordance with Fick’s Law, the change in chloride ion concentration in the weathering steel patina over time is related to the gradient between the surface chloride concentration and the chloride levels within the patina. The rate at which the higher levels of surface chlorides diffuse into the patina layer is a function of time, the permeability of the patina, and temperature. Following the deposition of chlorides onto a weathering steel surface, Fick’s Law suggests a portion of the chlorides will permeate into the patina layer in order to seek equilibrium. Over time, diffusion of chlorides through the patina would gradually result in more or less uniform chloride concentrations throughout the thickness of the patina.

Because of the surface-based nature of the CHLOR*TEST and the corresponding low extraction efficiency on porous weathering steel, quantitative comparisons of data between different patina specimens are not practical. The fact that many of the chlorides in most patinas reside beneath the surface, combined with the range of patina surface conditions and the possible change in surface salt deposits over time, makes meaningful bridge-to-bridge, element-to-element, and time-to-time comparisons based on field chloride results infeasible.

Chloride Testing Summary. Chloride testing's usefulness as part of a regular bridge inspection and maintenance regimen appears to be very limited. The extraction efficiency of the field chloride test is too low to allow quantitative comparisons between patinas to be made with any degree of confidence in their accuracy. Given the complexity and variability of salt deposition, diffusion, and retention in weathering steel, it is our opinion that field measurement of chloride levels on bridges will yield little information to aid in predicting their future long-term performance.

Taken collectively, the chloride tests performed during our Iowa field work demonstrate that patina deterioration is the result of chloride exposure in areas that are not sufficiently cleaned by natural washing. While the presence of chlorides undoubtedly accelerates the corrosion process and leads to formation of harmful rust phases in lieu of the desired uniform, tightly adherent protective patina, field chloride testing yields insufficient information for evaluating patina performance and predicting long-term future behavior. Accordingly, it is our opinion that field chloride testing will not be effective in prioritizing deteriorated structures for maintenance. Instead, the focus of any bridge maintenance effort should be directed at identifying and eliminating conditions that promote corrosion due to chloride contamination, such as conditions that prolong time of wetness and speed chloride penetration.

Color Testing

Color testing was performed on a limited number of bridges during the Iowa field investigation. This testing was undertaken as another means of quantitatively supplementing visual inspection results and for potential correlation with the patina performance index rating scale. After utilizing the color testing device on several bridges and evaluating the results, WJE elected to discontinue color testing in favor of more productive tests.

Color Test Procedures. A Konica Minolta CR400 Chroma Meter Colorimeter was used to obtain color measurements directly on the surface of the patina. When placed against the patina, the color testing device flashes a light through its 8mm diameter aperture onto the weathering steel, recording the levels of each primary light color component returned by the surface. These values are then interpreted in a computer to derive a corresponding uniform shade representative of the test area.

Evaluation of the Color Tests. It was anticipated that a patina color could be quantified in an effort to correlate patina color to performance. The color test results revealed that this would not be practical for evaluation of patina performance. This determination is due to the testing scale rather than inaccuracies of the testing equipment. The small area considered by the test still contains significant color variation due to the flaky, semi-crystalline nature of rust products comprising the patina surface. However, the color variation of interest is present on a much larger scale, such as mottling and non-uniform patterns in the patina visible from a distance. The color test measures color on a scale where meaningful comparisons from one patina area to another are not possible. Specifically, areas of good patina and bad patina might still possess similar local color patterns on rust product flakes, but when viewed at arm's length the two regions could appear markedly different.

Color Testing Summary. Color test locations on individual bridges are noted in Appendix C, when applicable. In general, WJE performed a cursory review of the results using computer post-processing of the color data and determined that the information collected did not yield meaningful information about patina performance. More specifically, the collected color test data for a given sample corresponded to a shade of brown identified by a computer, but comparison of these shades did not provide meaningful information about the relative color variation in the weathering steel patina from regions of good protective behavior to regions of poor protective behavior. One exception was noted in this pattern. Areas of poultice corrosion, or heavily chalked surfaces, demonstrated a consistent, significant color difference compared to non-chalked patinas, as measured by the Chroma Meter. However, this difference was also readily discernible with the naked eye in all cases. In light of the fact that the color test does not yield practical information, the significant cost of the test device, and the ability to distinguish important trends in patina coloration with the naked eye, the color testing equipment is deemed to not be a practical method to include as part of a routine field inspection program.

Physical Sampling

In addition to the field tests described above, WJE removed physical samples of weathering steel for closer examination at our Northbrook laboratory. In all cases, these samples were collected adjacent to field tests, such as tape tests or chloride tests, to facilitate direct comparison of the results. Two types of physical samples were obtained during the field investigations in Illinois and Iowa: through-thickness cores of weathering steel members and scrapings of patina flakes. Both sample types could be used for chemical analysis of the rust phases; however, only the cores were tested for chloride content.

Physical Sampling Procedures. Steel cores were obtained at a total of five locations during our field investigation in Iowa. The core locations were carefully selected to provide variability of patina performance, field-measured chloride levels, and environmental conditions. At the request of Iowa DOT, steel cores were only removed from secondary bridge members such as diaphragms and cross-bracing, and the cores were taken from non-critical locations on these members. Core sampling was performed using a magnetic drill, and each sample was stored in a sample bag to prevent contamination. Core samples were removed at the following locations:

- 7774.0L065, first cross-frame from west over eastbound Army Post Road, bottom WT brace, stem of tee (Sample FS4).
- 7731.5R080, first cross-frame west of east abutment, between second and third interior girders from south fascia, bottom WT brace, stem of tee (Sample FS5).
- 7708.2O235, first diaphragm south of south pier, between second and third interior girders from west fascia, channel diaphragm, bottom of web (Sample FS7-over).
- 7708.5S235, over southbound River Road curb between fourth and fifth interior girders from south fascia, channel diaphragm, bottom of web (Sample FS7-under).
- 9811.3O035, between two center girders over northbound I-35 right shoulder, channel diaphragm, bottom of web (Sample FS 11).

WJE also obtained patina scrapings from various bridges in Iowa and Illinois. Typical scraping locations were in regions where substantial flaking or rust delamination was present; however, some scrapings of tightly adhered patinas were also retrieved for potential comparison in the laboratory. Scrapings were collected directly into sample bags using a stainless steel putty knife.

Evaluation of Physical Sampling. Sample removal allows for detailed laboratory investigation that is not possible in the field. Core sampling is the most effective, since all characteristics of the in-situ patina are preserved, including rust flake size, spatial distribution, flake orientation, adherence, voiding and pitting, and condition of the base steel substrate. In addition, all of the chlorides present throughout the thickness of the patina can theoretically be extracted from a core sample.

Scrapings are less effective than cores, but they are still useful for chemical composition tests and examination of the different rust phases present. Only the chlorides within and on the surface of the flakes are removed, so comparison to field chloride testing is limited due to the amount of chlorides that remain in-situ. Scraped flakes are also highly disturbed during removal, as these particles tend to break and will not retain any of their spatial distribution or orientation.

Physical Sampling Summary. Coring locations are noted for each bridge studied in Appendix C, as applicable. Since scrapings were not used in the laboratory testing program, they have not been included in Appendix C. Physical sampling is not a practical method of evaluating patina performance as part of a field inspection program; however, it has been used here to evaluate the effectiveness of the other test methods employed in this study. Discussion of laboratory tests performed on collected core samples is included in the next section of this report.

Laboratory Testing of Physical Samples

The physical core samples obtained from the Iowa field investigation were subjected to various laboratory tests, including chloride testing, scanning electron microscopy with energy dispersive x-ray spectroscopy (SEM/EDS), Fourier transform infrared spectroscopy (FTIR), and x-ray diffraction (XRD). The results of the laboratory testing are provided in Appendices D and E.

Laboratory Testing of Chlorides. Water-soluble chloride contents were measured on five core samples removed from weathering steel bridges in Iowa. Prior to testing, the cores were cut in half axially to separate the two faces, so that the chloride measured could be related to the face tested. For each sample, only one face was tested, which corresponded to the surface where field chloride testing was performed. The samples were immersed in deionized water and boiled for one hour. The extract was cooled, decanted, and brought to a consistent volume for each sample. Chloride content was measured by titration with silver nitrate as described in ASTM C 1218, *Test Method for Water-Soluble Chloride in Mortar and Concrete*. Results are provided in Appendix D.

Comparisons of the field and laboratory test results indicate that the field chloride tests have a low extraction rate, on the order of approximately 10 percent or less. The chloride testing performed in the laboratory utilizes boiling to extract surface chlorides as well as chlorides trapped within the patina layer. Field chloride testing is performed on a non-uniform surface with microscopic pits and variable roughness. As a result, the field chloride tests have limited effectiveness in removing chlorides trapped within the patina layer or the rust matrix. The concerns presented in the field chloride testing section above are confirmed using the laboratory test methods. Therefore, field chloride testing is not recommended for routine bridge inspections.

Laboratory Analysis of Corrosion Product. Laboratory analyses of the weathering steel corrosion product, including SEM/EDS, FTIR, and XRD was performed on three weathering steel core samples. Detailed results of each analysis method are summarized in Appendix E. Literature research has indicated that laboratory testing of the corrosion product on the steel can provide information regarding the protectiveness of the patina. The primary objective of this testing was to observe the amorphous and crystalline compositions of the corrosion product to determine if compositional analysis using laboratory techniques could provide useful information regarding the protectiveness of the patina on the steel.

Patinas on weathering steel are not always protective; the development of the patina depends on many factors, including age, number and duration of wet/dry cycles, atmospheric humidity, and the presence of corrosion accelerators, such as chlorides and atmospheric pollutants. While the detailed laboratory analyses of the corrosion product were in general agreement with the published literature, the core samples typically contained both the amorphous and crystalline phases of the rust layer and these phases were intermixed. In addition, elements such as Cl^- were identified, but it is difficult to quantify and compare the relative quantities of these elements between core samples. Because physical sampling and laboratory testing is not practical and only represents an isolated area of the patina surface, it is not recommended as a routine inspection method for the Iowa DOT.

Evaluation of High-Pressure Washing

WJE performed experimental pressure washing on selected portions of various bridges while conducting the field investigation in Iowa. The Iowa DOT is specifically interested in the efficacy of pressure washing of weathering steel bridges as a means of extending their useful life. Accordingly, WJE systematically washed sections of bridge girders at high pressure with both plain water and with water enhanced using CHLOR*RID International's CHLOR*RID salt removal solution. The washing was performed to evaluate the immediate effects on the weathering steel patinas. To assess the impact, WJE performed detailed testing of the subject areas before and after washing. In total, WJE washed portions of five structures during the course of our Iowa field investigation.

Reportedly, the Iowa DOT performed washing of approximately 21 weathering steel bridge structures in 2008. All bridges were located along the I-235 corridor through central Des Moines. The bridge cleaning was performed in accordance with Section 2427 of the Iowa DOT *Standard Specifications for Highway and Bridge Construction*, which involved a flushing water wash (1,000 psi maximum) using a minimum flow rate of 5 gallons per minute. It is our understanding that the bridge cleaning specification is typically used to flush dirt, debris, and foreign material from the bridge without damaging the paint coating.

Field Washing Procedures. Washing of the bridges followed a standardized procedure developed as part of this project to facilitate meaningful data collection and performance assessment. At each location, the patina surface was washed at 3,500 psi with the nozzle approximately 12 inches from the steel surface. Washing of the patina surface proceeded at a rate of approximately three square feet per gallon. Two different nozzles were evaluated to determine the ability of the high-pressure spray to remove loose patina flakes. Initial washing experiments utilized a 40° spray angle, while later attempts used a 0° nozzle.

Wash water was obtained from potable (tap) sources, and was stored in drums on the bed of the bucket truck. In instances where CHLOR*RID was used, it was mixed in a separate container at a concentration of 1 gallon of CHLOR*RID per 100 gallons of water, per the manufacturer's recommendations.

Tests performed on the washed areas included tape and chloride testing before and after the wash. The washed areas were permitted to fully dry prior to re-testing. WJE typically washed the bottom portion of the girder webs and the top of the bottom flange, as both locations tended to hold varying but significant amounts of chlorides. On occasion, stiffeners, braces, and other surfaces were washed for comparison purposes. Figure 34 shows the high-pressure washing in progress.

Evaluation of Bridge Washing. High-pressure washing of weathering steel bridges may be feasible and beneficial as part of a maintenance regimen. For this field study, a coverage rate of approximately three square feet per gallon was used, and the 3500 psi washing equipment had a flow rate of approximately 3.7

gallons per minute. This resulted in a coverage rate of about 11 square feet per minute. This coverage rate appeared to be sufficient for the purposes of this experimental washing.

It was found that a 0° nozzle was much more effective at removing loose rust flakes from a moderately deteriorated patina in order to clean the surface down to the tightly adherent protective layer. The exception to this observation was on the top surface of girder bottom flanges with a significantly delaminated patina layer and/or substantial poultice corrosion. While the 0° nozzle removed the majority of the loose laminations and scale, a portion of the deteriorated patina layer remained. In this case, more complete removal of loose rust could be achieved with a higher pressure. While the 0° nozzle provided much better mechanical action to remove loose scale and flakes from the patina surface compared to the 40° nozzle, it also required extra diligence during the wash to ensure complete coverage of the intended area at the allotted rate. The 40° nozzle demonstrated that it was not adequate to remove surface rust flakes at the 3500 psi wash pressure, but it easily provided the required coverage.

Based on the test wash comparisons performed on the weathering steel bridges using the CHLOR*RID solution, it was found that CHLOR*RID did not appear to provide any measureable benefit over plain water in terms of chloride ion concentration reduction. Based on chloride test results before and after washing of adjacent areas of a girder exposed to similar conditions, both water washing and CHLOR*RID solution washing yielded significant reductions in measured chloride concentrations. However, the CHLOR*RID solution did not further reduce chloride concentrations beyond water washing alone. These results were consistent regardless of surface preparation or washing of patinas with varying performance index ratings. Accordingly, WJE does not recommend that Iowa DOT use enhanced washing solutions in conjunction with a washing program at this time, given the additional cost of the enhanced washing products.

High-Pressure Washing Summary. Results for each washing experiment are summarized for their respective bridges in Appendix C. The high-pressure wash (3,500 psi) used during the field investigation was considerably higher than the washing pressure specified in the existing Iowa DOT bridge cleaning specification (1,000 psi maximum) because there was no concern for damaging existing paint coatings. In general, high-pressure washing was found to be an effective means of reducing surface chloride ion concentrations on weathering steel patinas. Chloride testing from the five structures washed confirms that relatively moderate and high chloride levels (as determined by CHLOR*TEST results) are substantially reduced with washing; however, measurable chlorides were typically not completely eliminated. This may indicate that washing primarily removes chlorides present on or near the surface of the patina, while latent chlorides remain beneath the surface in the pores and voids of a deteriorating patina. WJE noted that areas where the patina was ground to bare pitted steel with a wire wheel often retained significant (albeit reduced) chlorides after washing; chlorides trapped within the rust matrix itself or deeply worked into the pits and voids of the adherent portion of the patina pose a significant removal challenge.

The most effective washing results were achieved with the 0° nozzle. Unlike its 40° counterpart, the 0° nozzle was able to remove substantial amounts of loose, deteriorated rust flakes from the patina surface, leaving the underlying denser, more adherent layer behind. In addition to removing the loose rust flakes and scale from a deteriorating patina, all chlorides and dirt trapped within these particles are also removed. The chlorides and dirt on the surface have a tendency to retain moisture, which prolongs periods of wetness and tends to accelerate patina deterioration. It is anticipated that a slightly wider nozzle, such as 15°, would likely provide adequate mechanical action to remove loose flakes and other debris from most patina surfaces while promoting slightly more uniform coverage of the wash area.

If performed immediately following the winter deicing season, washing will remove many of the surface chloride contaminants that likely will subsequently migrate into the protective oxide layer during the spring, summer, and fall, as predicted by Fick's Law. As a result, washing after the winter season, before the newly deposited chlorides have a chance to do damage, may promote development of a protective oxide layer on moderately deteriorated patinas and improve long-term performance. If such washing is repeated on a regularly scheduled basis, the progression of corrosion-related deterioration may be slowed from reaching more advanced stages of deterioration. It is also likely that the maximum benefits of washing are achieved on newer weathering steel structures, where latent chloride build-up has had less time to progress. In relatively young bridges, early-age washing of surface chlorides may slow penetration and chloride build-up deep within the patina; however, further study is needed to confirm this.

In short, high-pressure washing after the winter season will likely help to reduce surface chlorides that have the potential to migrate into the protective patina. In addition, loose rust flakes, dirt, debris, and other contaminants, which often retain moisture and prolong the periods of wetness, are removed during high-pressure washing. The benefits of washing a particular weathering steel bridge are dependent on the condition of its patinas as well as its age, size, environment, and location, and these factors should be weighed against the potential costs and inconveniences associated with washing, such as access and lane closures. In addition, consideration should be given to selective washing of problem areas on a bridge, which may be both practical and effective as a maintenance technique. Based on the information gathered during this study, high-pressure washing with enhancement solutions does not appear to provide additional benefits compared to water washing alone.

SUMMARY AND RECOMMENDATIONS

Primary Factors Influencing Weathering Steel Bridge Performance

The performance of weathering steel depends on the proper formation of a dense layer of corrosion product to protect the steel from further atmospheric corrosion. Initially, the corrosion rate of weathering steel is similar to that of plain carbon steel; however, wetting and drying cycles, or natural weathering, causes weathering steel to develop a dense oxide layer, or patina, on the exposed surfaces. This dense, well-adhered patina helps to slow additional rust formation and the corrosion rate of the weathering steel stabilizes. The development of the weathering steel patina may be influenced by factors such as:

- Environments
  - Urban, suburban, rural, marine, industrial, etc.
  - Humid or dry climates
- Microclimates
  - Sheltered or bold exposures
  - Structure geometry (orientation, angle of exposure)
  - Atmospheric pollutants
  - Time of wetness
  - Traffic below (volume, speed, type, etc.)
  - Chloride Exposure
- Design details

Weathering steel structures will perform best in Iowa when they are placed at sites with bold exposures (exposed to sun and weather without sheltering), are not exposed to chlorides or extended periods of wetness, and are properly detailed to avoid ponding moisture, dirt, and debris. Nearly all of the weathering steel bridges in Iowa have been constructed in the past 20 years. Based on the observations during our field investigation, these structures have been properly detailed in accordance with the recommendations presented in the FHWA Technical Advisory, including using narrow flange widths, coped stiffeners, water diverter plates, painted girder ends, and integral abutments, as well as eliminating unnecessary cross frames, stiffeners, lateral bracing, and scuppers. These improved design details help to reduce potential sources of chloride contaminated water as well as limit areas where water is allowed to pond on the steel surfaces.

Because the vast majority of the bridges in Iowa are properly detailed, we believe the performance of weathering steel structures in Iowa can be reduced to three primary factors: 1) heavy exposure to deicing salts, 2) extended periods of wetness, and 3) the exposure environment. These three factors often go hand-in-hand. For example, bridges in urban environment often have a sheltered exposure and are subjected to chlorides and wetness when traffic "spray" causes chlorides, moisture, and debris to be deposited on the bridge structure. In rural environments, the bridges may still be subjected to salt/moisture spray from traffic below; however, the open land surrounding the bridge site results in a bolder exposure as the structure is exposed to sun, wind, and rain from various directions. As a result, weathering steel structures in rural environments are performing better than structures in urban environments.

While these three primary factors affect the overall patina development at various weathering steel bridge sites, these factors also affect the development of the patina at various locations within a single bridge structure. In the "splash zone," chlorides and moisture often settle onto the top surface of the bottom flange along with dust, dirt, rust flakes, bird droppings, and other debris. This contaminant layer is commonly referred to as a "poultice" that retains moisture and keeps chlorides in close contact with these horizontal surfaces. As a result, poultice corrosion was a common observation on horizontal surfaces above traffic or in areas where water and dirt could migrate and settle outside of the splash zone. Conversely, the fascia girder is often exposed to direct sun and rain that results in frequent washing of the patina. This frequent natural washing reduces the chloride contamination on these surfaces, thus improving the performance of the weathering steel patina. The Iowa bridge structures visited as part of this project exhibit varying degrees of patina performance.

Recommended Inspection Techniques for Weathering Steel Bridges in Iowa

One of main objectives of this project is to develop inspection and testing techniques that can be used to evaluate the performance of a weathering steel patina. Research indicates that it is possible to measure chloride deposition rates at a particular site to determine if the site is suitable for a weathering steel bridge structure. However, in this case, the bridge structures are already in service, so it is necessary to develop an inspection technique to evaluate the patina and distinguish between good and poor patina performance. In order to achieve this objective, WJE utilized several inspection techniques during the field investigation, including visual inspection, tape adhesion testing, chloride testing, color testing, and physical sampling. The most effective, efficient, and practical patina evaluation techniques were found to be visual inspection and tape adhesion testing.

Visual Inspection

Visual inspection of weathering steel is highly effective for making an overall assessment of patina performance and trouble-shooting problem areas. It is a fast process, and was often found to be adequate to describe conditions on the bridge independent of other testing. WJE found that after inspecting several bridges exhibiting a range of patina conditions, we were often able to confidently assign patina index ratings based on a visual survey alone. WJE also found that, even with two inspectors working independently on the same structure, there was consistency in visual ratings after working together on only a few bridges. This suggests that consistency in visual inspections is achievable in the context of a larger field inspection/inventory program, even with multiple inspectors, provided some basic training is given. Therefore, visual inspection of the weathering patina is recommended to be performed in conjunction with the National Bridge Inspection Standards (NBIS) routine inspections performed every 24 months.

The visual inspection of weathering steel should focus on specific characteristics of the appearance in order to consistently rank the condition of the patina using the proposed rating scale, discussed later. These appearance characteristics include the overall shade and tone of the patina color, uniformity of the coloration (or lack thereof), texture, adherence, as well as size and spatial distribution of the rust flakes on the surface of the patina. Because adherence and approximate size of any rust flakes on the patina surface are key parameters in consistently ranking the patina, a small scale held against the region of patina being considered proved helpful in quickly estimating average flake size.

WJE visually rated the patinas in terms of both overall and localized performance. Due to the presence of a possible poultice layer on the top of horizontal surfaces, excessive corrosion or poor patina performance is best detected at close range. To ensure consistent rating of patina performance from bridge to bridge, WJE typically observed the corrosion products up close using an aerial lift or by closely approaching areas near the abutment slope walls. Whenever possible, WJE inspectors tried to be within arm’s length of the patina to gauge its adherence, texture, and flakiness. Although an arm’s length inspection is not required for routine inspections of multi-girder structures, inspection from this distance allowed other tests to be performed, such as tape adhesion testing, as discussed below.

Once close-up observations of patina performance were made, WJE was able to extend ratings to other portions of the bridge observed at greater distances by visual comparison. Overall ratings indicate performance of a bridge structure on average; localized ratings help in quantifying the performance of the weathering steel at trouble spots and in identifying the range of conditions present on a given bridge.

Tape Adhesion Testing

Though visual inspection is an excellent means of evaluating Iowa weathering steel bridges, WJE believes tape adhesion testing is also a simple, effective, and reliable method of patina evaluation that will facilitate consistency in the inspection program. This type of supplemental testing is beneficial to the bridge evaluation process because it provides confirmatory evidence to supplement the visual inspection findings. In addition, it can serve as a permanent record for comparison with future inspections.

WJE recommends including tape adhesion testing on weathering steel bridges as part of the routine NBIS inspections performed every 24 months. Tape testing is a useful tool to provide verification of visual patina index ratings, track patina performance on different surfaces within a structure, and allow more detailed comparison of rust flake size and density to other parameters such as chloride ion concentration. For patinas in generally good condition, small flake sizes on the tape samples can be accurately measured using a handheld 10x magnifying lens with a built-in measurement scale.

By storing the tape specimens inside sample bags, the rust flakes can be examined and measured without disturbing them. The tape samples can be used to assess the flake size and density and assign the patina a rating for prioritization purposes. In addition, the tape test samples provide a permanent record of the non-adherent rust particle size and distribution for future reference after the field work is completed.

Comparison of tape adhesion test samples from different inspections may provide useful information to determine if the patina condition is worsening or stabilizing.

Chloride Testing

Chloride testing's usefulness as part of a regular bridge inspection and maintenance regimen is very limited. The extraction efficiency of the field chloride tests is too low to allow quantitative comparisons between patinas to be made with any degree of confidence in their accuracy. Given the complexity and variability of salt deposition, diffusion, and retention in weathering steel, it is our opinion that field measurement of chloride levels on bridges will yield little information to aid in predicting their future long-term performance.

Research indicates that there is a correlation between chloride contamination within a patina layer and the size of the loose rust flakes on the surface. In other words, chloride ions accelerate the growth of the rust layer and increase the rust particle size, which is not beneficial to the formation of a protective patina. Therefore, visual inspection techniques, discussed above, are an effective way to approximate relative chloride contents within weathering steel patinas.

Confirmation of this correlation was noted on different occasions during this project. For example, our inspections included a small pedestrian bridge in a suburban Illinois park. This bridge structure was put into service just before the winter of 2011/2012, approximately 10 months prior to our investigation. The use of deicing salts during the winter months was found to have a noticeable impact on the development of the patina. On the truss top chords, above the area exposed to deicing salts, the patina was well adhered, had a reddish brown color, and had a small rust flake size (Figure 5). On the other hand, the truss floor beams below the wood plank deck were directly exposed to deicing salts and were found to have a streaky non-uniform color and a larger rust flake size (Figure 4). The comparison between these two conditions indicates that visual observations and tape adhesion testing can provide relative information regarding the chloride contamination of the patina.

A second example noted during this project occurred during the inspection of US-75 over Business-75 and railroad in Woodbury County (Structure 9799.5L075). This structure was one of the few inspected during the field investigation that exhibited regular cracking in the concrete deck that allowed chloride contaminated water to leak onto the west fascia girder. Typically, the fascia girders are exposed to frequent, natural washing and drying that improves patina performance. At this structure, the areas of good patina on the fascia girder were interrupted by areas of non-uniform black discolorations and a corresponding increase in rust flake size, as shown in Figure 35. This pattern again indicates that the visual appearance of the patina is a good indicator of relative chloride contamination.

Taken collectively, the chloride tests performed during our Iowa field work demonstrate that patina deterioration is the result of chloride exposure in areas that are not sufficiently cleaned by natural washing. While the presence of chlorides undoubtedly accelerates the corrosion process and leads to formation of harmful rust phases in lieu of the desired uniform, tightly adherent protective patina, field chloride testing yields insufficient information for evaluating patina performance and predicting long-term future behavior. Accordingly, it is our opinion that field chloride testing will not be effective in prioritizing deteriorated structures for maintenance. Instead, the bridge inspection effort should focus on visual observations and tape adhesion testing, which can be correlated to relative chloride levels.

Proposed Inspection Rating Scale

Another main project objective was to develop a general prioritization of weathering steel bridges in Iowa. In our opinion, Iowa DOT would benefit from using patina ratings similar to the one employed in our field investigation of various weathering steel bridges. Teams of inspectors could quickly and accurately evaluate the condition of the patinas on many bridges with consistency; tape adhesion testing would help calibrate and corroborate visual assessments. Bridge prioritization could then be performed based on the results of the patina rating, visual inspection, and tape adhesion testing. The main goal would be to consistently rate weathering steel patinas so the worst performers can be identified.
During the course of the project, WJE utilized a patina rating index that was based on work performed in Japan to correlate patina color, uniformity, and rust flake size to its performance. The patina rating index served as a useful tool in several contexts. In addition to providing a consistent quantitative description of the overall performance of a weathering steel bridge, it identified the range of conditions present. This type of rating also facilitates comparison of trends in weathering steel behavior across multiple bridges or over multiple inspection periods.

WJE proposes to utilize a similar patina rating system that considers the patina color, uniformity, adherence, and rust flake size. WJE also proposes to base the rating scale on the current format used during routine NBIS inspections for steel superstructures. This proposed patina rating scale ranges from a rating of *8—Excellent* to *3—Serious*, and is shown in Appendix F along with a condition description and example photographs for each rating.

Similar to NBIS routine inspections, WJE recommends assigning an overall patina rating to the entire bridge structure. This overall rating would represents the typical patina conditions in a structure, but also give due consideration to problem areas of the patina that may not be performing as desired. In addition, the patina evaluation and rating should also focus on potential problem areas or unique conditions as discussed below.

Areas of Focus

WJE typically noted a wide range of patina conditions throughout a bridge structure or even at different faces of the same girder. However, these observed conditions are often consistent along the length of the girder, with slight variations between locations over traffic or near the abutments. In order to evaluate the overall condition of the patina for a bridge structure, WJE recommends evaluating the patina at each of the following typical locations both over traffic and near an abutment:

- Fascia girder
    - Web exterior face, mid-height
    - Web exterior face, bottom
    - Top of bottom flange, exterior face
    - Bottom of bottom flange
- Interior girder and/or interior face of fascia girder
    - Bottom of bottom flange
    - Top of bottom flange
    - Bottom of web
    - Web mid-height

It should also be noted the side of the interior girders facing traffic often has different conditions than the opposite side facing away from traffic. However, the side that was performing better did not correlate to whether it faced toward or away from traffic, which indicates that it may be a result of environment, exposure, and microclimate factors.

Once a patina evaluation is made at the typical locations recommended above, WJE recommends performing patina evaluations at specific known areas of poor patina performance, potential problem areas of the bridge, or other unique locations. For example, potential problem areas could include leaking deck joints, areas with visible salt staining, low points in the bridge slope, the vicinity of drainage scuppers, and/or poultice layers or chalking on the top of the bottom flange and other horizontal surfaces. Unique locations on a bridge structure may include areas below cracks in the concrete deck that are exposed to chloride contaminated water (Figure 35) or fascia girders that are subjected to direct snow/salt spray from an adjacent roadway (Figures 28 and 29).

Use of the proposed rating system can be made more effective by including a description and comparison of the effects of influential parameters (e.g., bridge location, geometry, traffic conditions and salt exposure, etc.). Therefore, Iowa DOT may consider developing an inspection form to provide background information for the patina ratings, as this information may provide insight for a high or low rating or explain the cause for observed problem areas. Possible inspection form fields include, but are not limited to:

- Age: Year built, year opened to traffic
- Structure type: Simple, continuous, cantilever span
- Expansion joint type
- Service on, service under
- Environment: industrial, urban, suburban, rural
- Location near: chemical plants, refineries, polluted water
- Estimated salt use on bridge, under bridge
- Exposure: bold, sheltered, tunnel effect
- Clearance below
- Traffic on bridge and below: number of lanes, traffic counts, speed, % trucks
- Patina condition
    - Oxide: Tight, dusty, flaky, laminar
    - Color: Brown, orange, black
    - Uniformity: uniform, non-uniform, streaked
    - Texture: Smooth, granular, coarse
    - Pit depth, if present
- Patina rating

Recommendations for Bridge Washing

The remaining main objectives of this project include initial studies to evaluate the effectiveness of water washing and to recommend a pilot program for bridge washing based on the prioritization of weathering steel structures. The benefits of frequent washing are evident from the weathering steel performance on the exposed surfaces of the fascia girders. Natural washing and drying by rain removes surface chlorides, cutting down on the rate of chloride ingress into the patina and promoting development of its protective oxide layer. While interior girders are exposed to moisture sources such as condensation, traffic spray, and fog, these sources of moisture do not serve as reliable mechanisms to wash contaminants away.

Effectiveness of Bridge Washing

Although high-pressure washing is not very effective in removing chlorides embedded in the patina layer, studies have found some evidence that periodic water washing may help to reduce the corrosion rate. At a minimum, the various studies agree that high-pressure washing will help to remove dirt, debris, loose rust flakes, and surface chloride contaminants that are often responsible for causing extended periods of wetness. This type of washing is also effective in removing much of the poultice layer of dirt and chlorides from horizontal steel surfaces, which often produces a sponge-like condition that may hinder the development of a protective patina.

The trial washing studies performed as part of this project found that high-pressure washing is an effective means of reducing surface chloride ion concentrations on weathering steel patinas and removing loose rust flakes that trap chlorides, dirt, and moisture. The most effective washing results were achieved with the 0° nozzle, which was able to remove substantial amounts of loose, deteriorated rust flakes from the patina surface, leaving the underlying denser, more adherent layer behind. In addition to removing the loose rust flakes and scale from a deteriorating patina, the chlorides and dirt trapped in these particles are also removed. It is anticipated that a slightly wider nozzle, such as 15°, would likely provide adequate mechanical action to remove loose flakes and other debris from most patina surfaces while promoting slightly more uniform coverage of the wash area.

In short, high-pressure washing after the winter season will likely help to reduce surface chlorides that have the potential to migrate/diffuse into the protective patina layer below. In addition, loose rust flakes, dirt, debris, and other contaminants are removed during high-pressure washing; these often retain moisture, prolong the periods of wetness, and accelerate patina deterioration. The benefits of washing on a particular weathering steel bridge are dependent on the condition of its patinas as well as its age, size, environment, and location, and these factors should be weighed against the potential costs and inconveniences associated with washing, such as access and lane closures. In addition, consideration should be given to selective washing of only problem areas on a bridge, which may be both practical and effective as a maintenance technique. Based on the information gathered during this study, high-pressure washing with enhancement solutions does not appear to provide additional benefits compared to water washing alone.

Pilot Washing Program for Iowa Bridges

The majority of the sample bridges WJE visited were performing adequately overall, with some localized areas of concern for future deterioration. The good news is that the bridges are properly detailed to limit areas of ponding water and reduce time of wetness. However, some of the urban bridges, particularly those over Interstates in Des Moines, exhibited advanced deterioration given their age, while two rural bridges surveyed had performed quite well over 40 years of service, with little cause for concern. While performance of the weathering steel bridges is quite good on the whole, washing is warranted on many structures to address problem areas or to clean the patina surface so it continues to perform as intended.

The findings of the field inspection and testing indicate that weathering steel bridges in Iowa can be generally prioritized based vulnerability to chloride contamination, location, exposure, and environment. For example, bridges in urban areas exposed to salt spray from an Interstate below are much more likely to exhibit unsatisfactory performance of the weathering steel patina than rural bridges with a bold exposure. Our field investigation revealed that the performance of the weathering steel bridges in Iowa, and consequently the patina rating, generally correlated to the exposure environment and service below the bridge structure. As a result, we developed the recommended baseline washing intervals for Iowa weathering steel bridge structures, which are summarized in Table 5.

Table 5. Proposed priority and washing interval for Iowa weathering steel bridges

Structure Type	Environment		
	Urban	**Suburban**	**Rural**
Grade separation, Interstate below	Priority 1 1 to 2 years	Priority 2 3 to 4 years	Priority 3 5 to 7 years
Grade separation, arterial or local road below	Priority 2 3 to 4 years	Priority 3 5 to 7 years	Priority 4 7 to 10 years
Stream crossing, rail crossing, or limited access road below	Priority 3 5 to 7 years	Priority 4 7 to 10 years	Priority 4 7 to 10 years

It is evident from Table 5 that the pilot washing program focuses on urban bridges with high speed and high volume traffic below. This is a result of the performance of bridge structures over I-235, I-80, and I-35 in Des Moines. Poultice corrosion on various surfaces has hindered the development of a protective patina, as shown in Figure 21. This patina layer was delaminated and easily removed from the steel surface, revealing another poultice layer below. The concern is that this type of poor patina performance will result in an endless cycle of patina delamination and a corrosion rate approaching that of regular unpainted mild steel, eventually resulting in significant pitting and section loss. As discussed earlier in this report, the AISI study investigated several bridges in Michigan in 1981 and 1994. During the initial inspection, the lower sheltered surfaces of two bridges were experiencing flaky/laminar rust, but it had not yet resulted in any measurable section loss; the age and condition of these bridges during the initial inspection is similar to that observed in the Des Moines area bridges over Interstates. When these bridges in Michigan were revisited in 1994 after being in service for 22 years, severe corrosion was observed over essentially the entire length of the bridges and painting was recommended. The high priority and frequent washing recommended for urban bridges over Interstates is an effort to slow the corrosion rate for these bridges and avoid remedial painting.

It should be noted that we recommend reducing the baseline washing interval for specific bridges to account for actual conditions, including low patina ratings, the presence of problem areas, unique conditions such as direct snow/salt spray from an adjacent structure, or tunnel like conditions (steep abutment walls, low clearances, and/or wide overpasses). Similarly, the baseline washing interval could be increased for structures performing well. For example, three bridge structures constructed in the 1970's were inspected during this project, and the performance of these structures was adequate given their age. While a one-time washing would help to remove the build-up of rust flakes that trap moisture and chlorides, these older bridges are located in rural areas, are performing well, and do not show indications of delaminations or pitting similar to that observed in the Des Moines area. Accordingly, these older rural bridges might safely reach the end of their useful service life without the added benefits of washing.

After the first round of NBIS routine inspections is performed and the patina ratings are obtained, the ratings will also provide guidance regarding the recommended course of action (Refer to Appendix F for proposed patina rating guidelines):

- Patina rating of 7 or above: continue periodic NBIS inspections to ensure patina is performing as intended.
- Patina rating of 6: continue periodic NBIS inspections to ensure patina is performing as intended, consider provisionary care such as periodic washing at baseline intervals.
- Patina rating of 5: careful evaluation to determine cause of detrimental corrosion in areas of poor performance, routine washing at baseline intervals or more frequently.
- Patina rating of 4: careful evaluation to determine cause of detrimental corrosion, routine washing more frequently than baseline intervals, monitoring, and consider painting if washing does not improve performance.
- Patina rating of 3: washing will likely not improve patina performance, painting should be scheduled.

WJE recommends high-pressure washing (3,500 to 5,000 psi) for the pilot washing program. In addition, a 15 degree nozzle is recommended to remove loose, non-adherent rust scale that traps moisture and debris while providing some coverage. A wash rate of approximately 3 to 6 square feet per gallon is recommended. Particular attention (such as higher pressure or extended wash times) should be given to problem areas, including poultice layers on bottom flanges and horizontal surfaces, areas of salt staining, or other areas where the patina rating indicates questionable patina performance. A higher pressure should also be used if needed to remove the poultice layer and patina laminations on the horizontal surfaces. Finally, washing is recommended as soon as practical after the winter deicing season, as washing will help to remove many of the surface chloride contaminants that likely will subsequently migrate/diffuse into the protective oxide layer during the spring, summer, and fall.

Potential Future Studies

During the development of this project scope, the potential for a second phase of work was discussed, if additional studies were warranted. Based on the findings of this study, we believe the following additional work would be beneficial to the Iowa DOT:

- Develop an inspection manual and/or training course material related to the weathering steel inspection, evaluation, and rating techniques discussed in this report.
- Evaluate the pilot bridge washing program to determine if the selected washing interval slows corrosion rates. This could be achieved by monitoring selected bridges with different patina ratings and conditions to evaluate patina performance over time, such as at each inspection and/or washing interval.
- Measuring chloride deposition rates, using test methods outlined in ASTM G92, for bridges with poorly performing patinas, such as the structures over Interstates in Des Moines. Chloride deposition rates could be evaluated to determine if weathering steel is appropriate for that environment and microclimate. Excessive salt deposition rates may indicate that weathering steel will not perform adequately and the washing program may not be an effective long-term solution to stabilize the corrosion rate of the patina.
- Review literature related to potential remedial measures that may be necessary for the bridges with the poorest performance (highest priority), including proper surface preparation techniques for painting existing weathering steel and the feasibility of patina surface modifications or rust stabilizing treatments.

WJE ENGINEERS ARCHITECTS MATERIALS SCIENTISTS

FIGURES

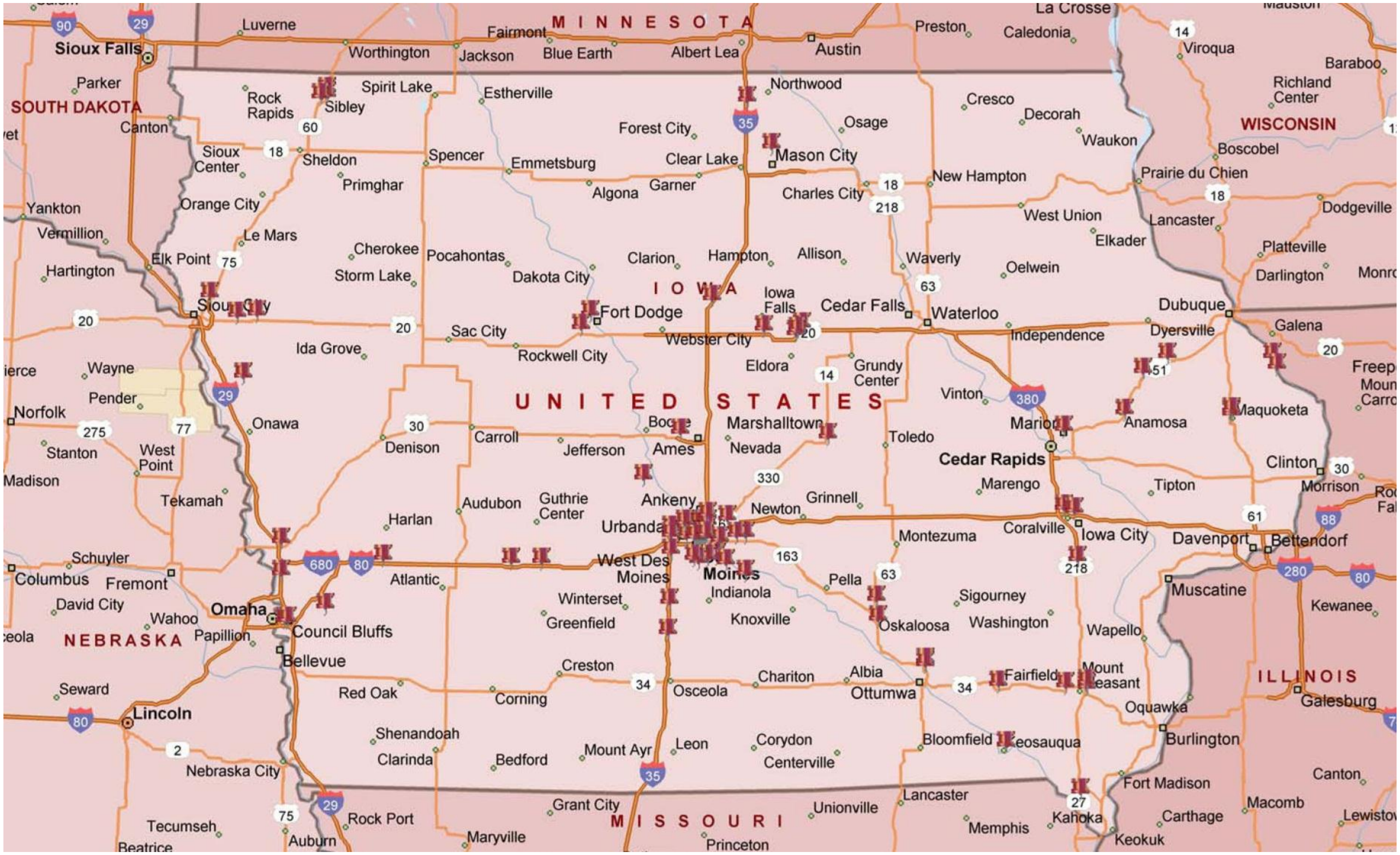

Figure 1. Map showing locations of Iowa DOT weathering steel bridge structures (each structure indicated by a thumbnail).

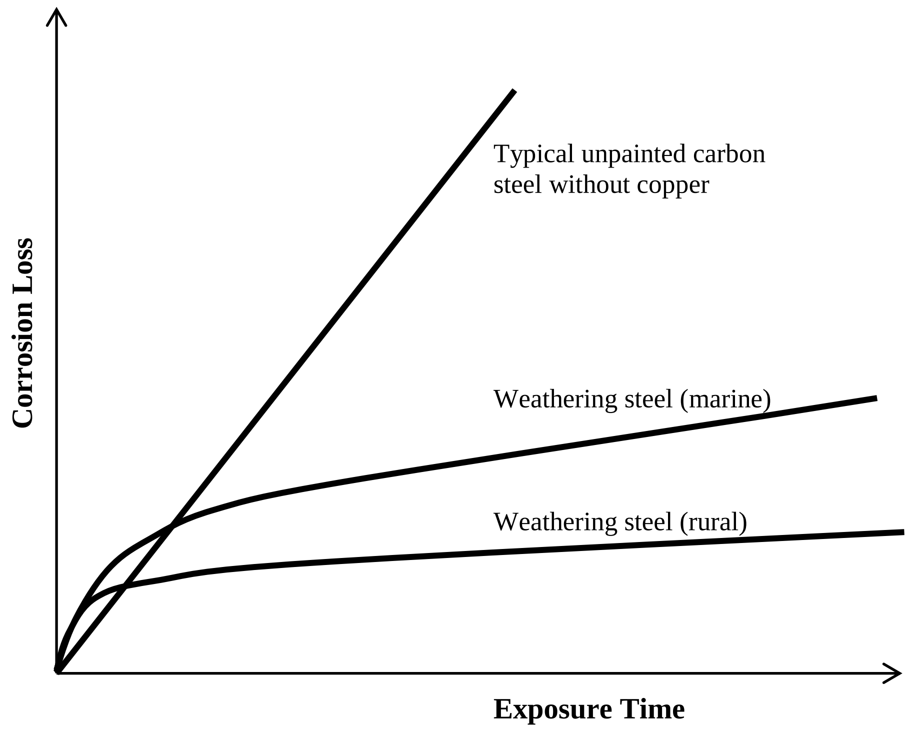

Figure 2. Schematic diagram showing the comparison between the corrosion rates for weathering steel and typical unpainted mild steel

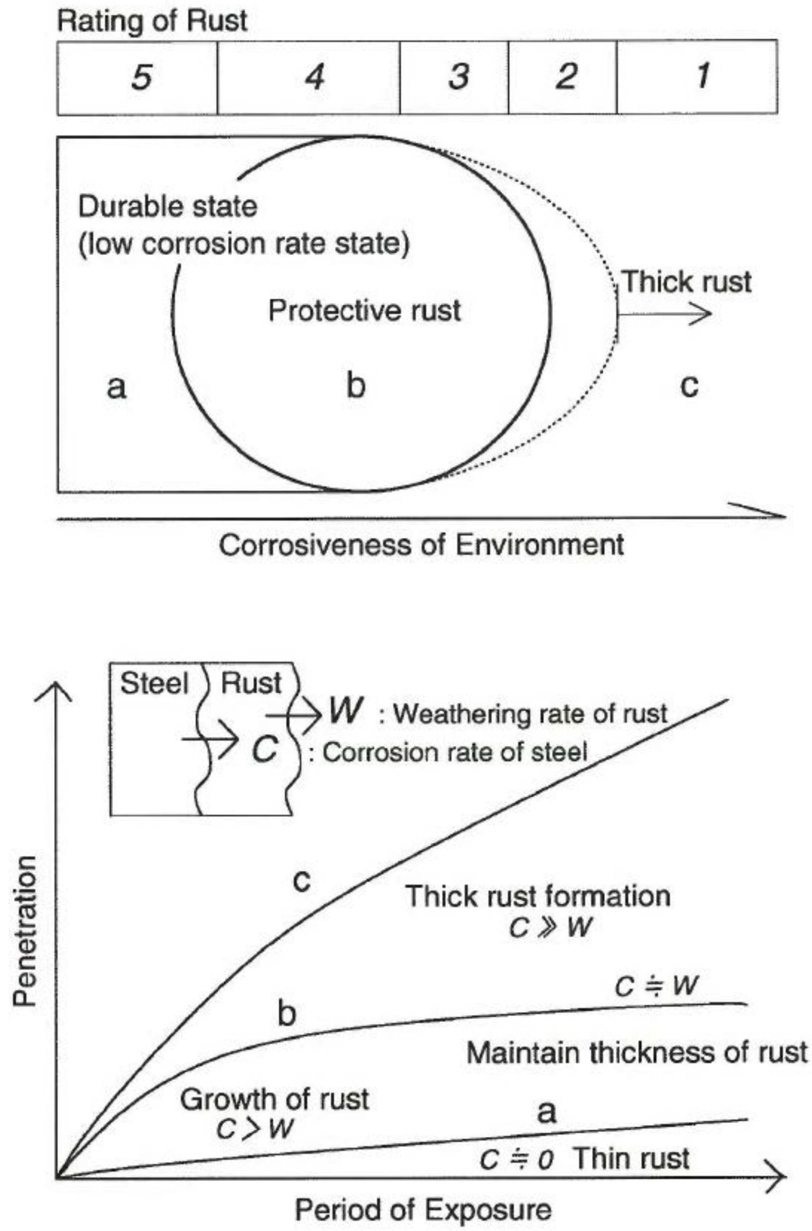

Figure 3. Schematic diagram showing the correlation between patina appearance index rating and corrosion rate.[3]

[3] Kihira, H. and M. Kimura, "Advancements of Weathering Steel Technologies in Japan," *Corrosion*, 67(9), 2011.

Figure 4*. Apparent nonprotective patina on the floor beams and bottom chords of this10 month old wood-decked pedestrian bridge.*

Figure 5*. Developing patina on pedestrian bridge in a suburban Illinois park. Note the adherent, small size of the patina rust particles, and the reddish coloration.*

Figure 6. Pedestrian bridge carrying a trail over the Des Plaines River in an Illinois forest preserve, with no apparent salt exposure.

Figure 7. Close-up photo of patina performance on the Des Plaines River pedestrian bridge; patina is dense and adherent, with small constituent rust particles.

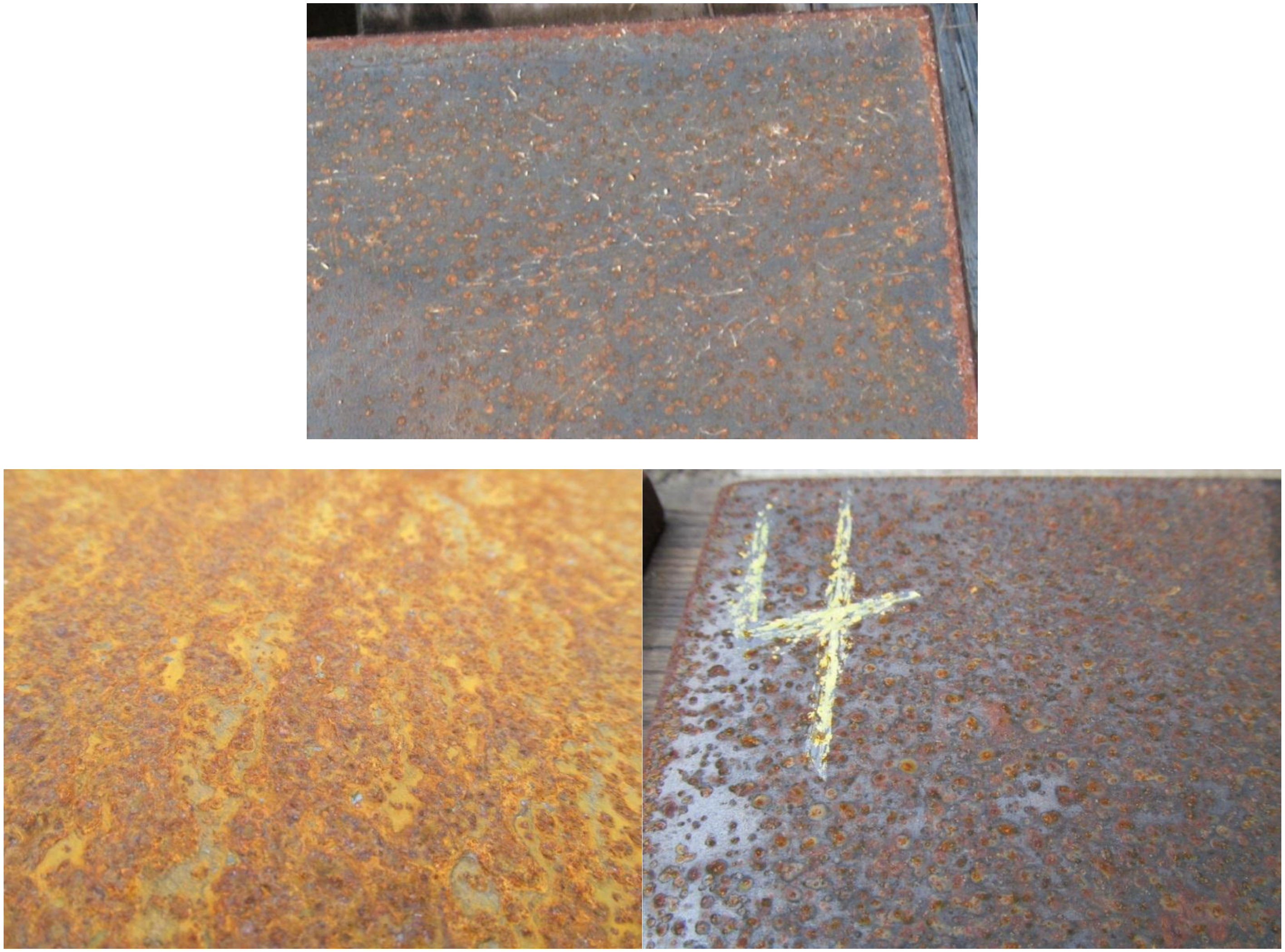

Figure 8. Close-up photos of plate condition before testing (top center), after salt spray (bottom left), and after deionized water spray (bottom right).

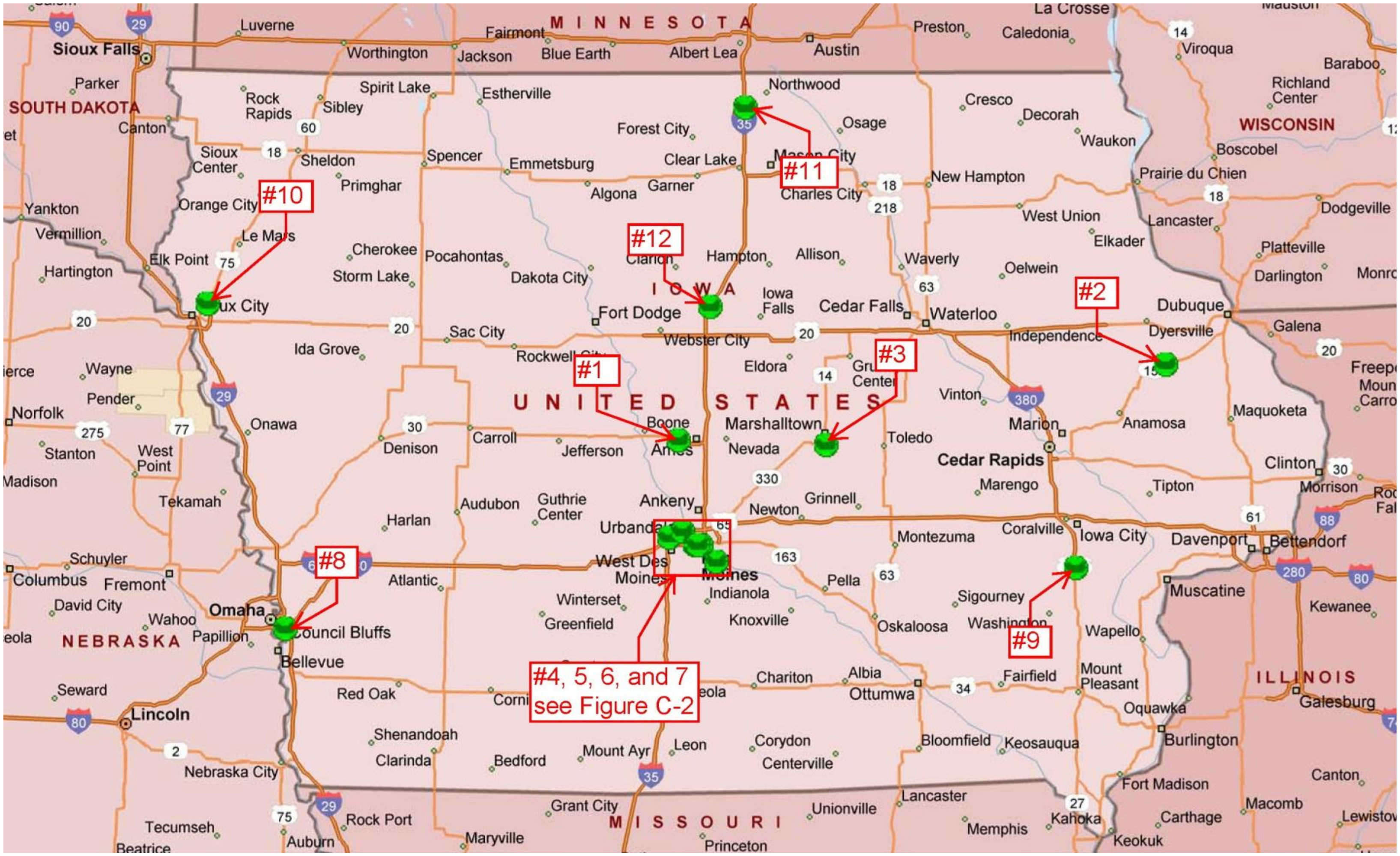

Figure 9. Map showing locations of weathering steel bridges selected for the Iowa field investigation (Field Selection number shown, refer to Appendix C).

Figure 10. *Typical framing for weathering steel bridges in Iowa, note narrow flange width, minimal use of transverse stiffeners, and lack of longitudinal stiffeners and bottom flange lateral bracing.*

Figure 11. *Typical detailing for weathering steel bridges in Iowa, note the narrow flange splice plate that prevents ponding water at the leading edge.*

Figure 12. Typical detailing for weathering steel bridges in Iowa, note the coped stiffener that allows water to pass.

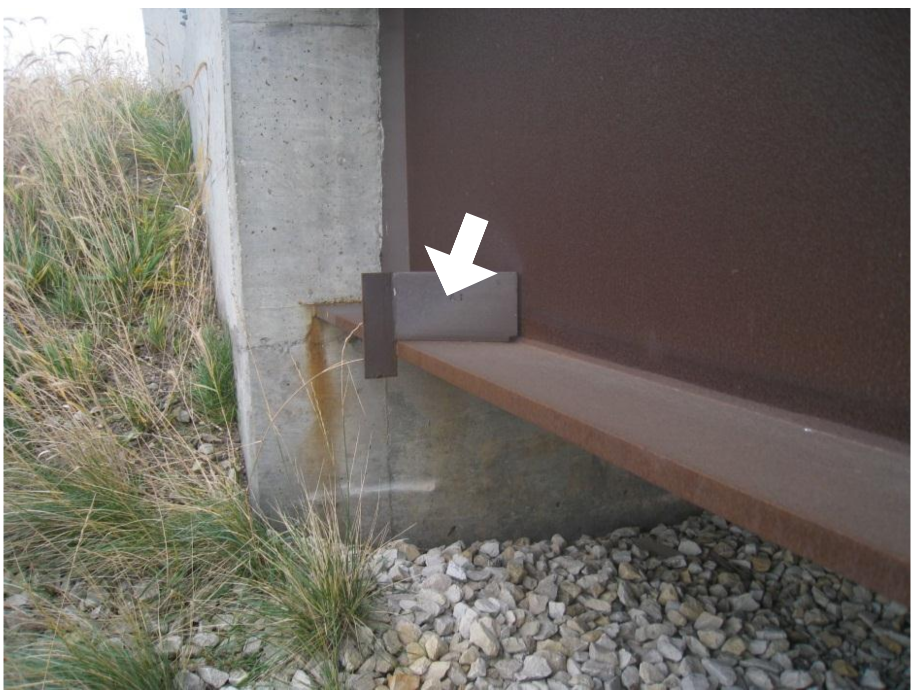

Figure 13. Typical detailing for weathering steel bridges in Iowa, note the water diversion plate (arrow), the painted ends of the girder, and the use of integral abutments.

Figure 14. *Typical detailing for weathering steel bridges in Iowa, note the use of integral abutments and the painted ends of the girder.*

Figure 15. *Typical detailing for weathering steel bridges in Iowa, note the painted ends of the girder.*

Figure 16*. Close-up photo of Category 5 patina taken from Illinois pedestrian bridge truss. Only isolated regions of Category 5 patina, likely due to mill scale, were observed on Iowa bridges.*

Figure 17. Close-up photo of Category 4 patina commonly observed on exterior web of fascia girder. Surface is textured but tightly adherent, and rust formations are small. No loose flakes are present.

Figure 18*. Close-up photo of Category 3 patina on bottom of interior girder web. Texture is less uniform but still generally adherent, with some small loose flakes.*

Figure 19*. Close-up photo of typical Category 2 patina on the underside of an interior girder bottom flange. Medium size flakes are easily peeled away with a fingernail.*

Figure 20. *Category 1 patina on top of an interior girder bottom flange; note the large, loose, thick flakes that cover virtually the entire surface. Section loss is not yet apparent in this case.*

Figure 21. *Poultice corrosion on an interior girder flange in downtown Des Moines. This is typical of conditions observed on the tops of many interior horizontal elements. Close examination and testing confirms this chalky film is primarily a mixture of dirt and salts.*

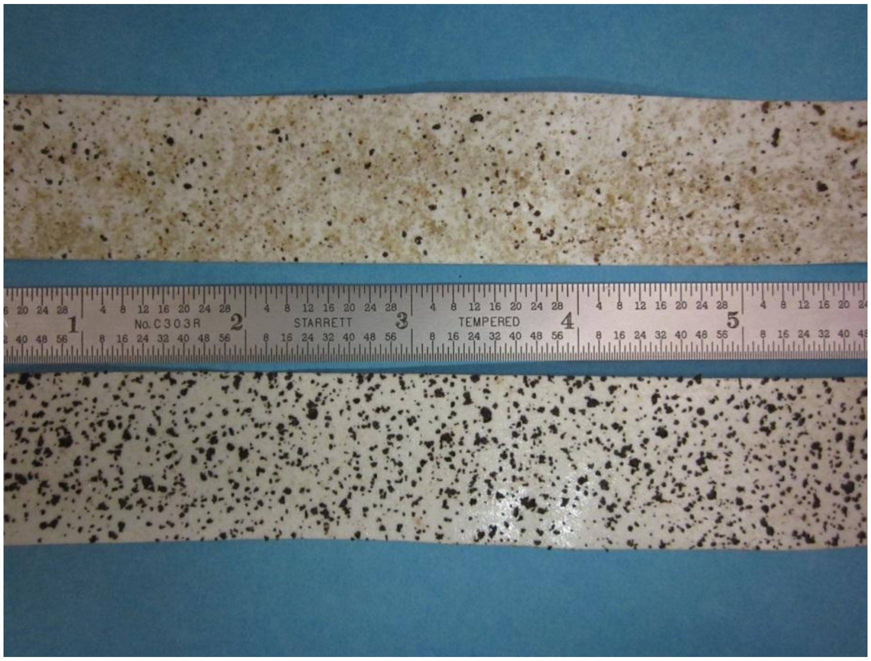

Figure 22. Tape test comparison of heavily chalked interior (top sample) and exterior (bottom sample) fascia girder bottom flange; note lighter coloration of salt and dirt deposits compared to rust flakes in poultice corrosion sample (top sample). Patina index rating for both of these specimens is 3.5.

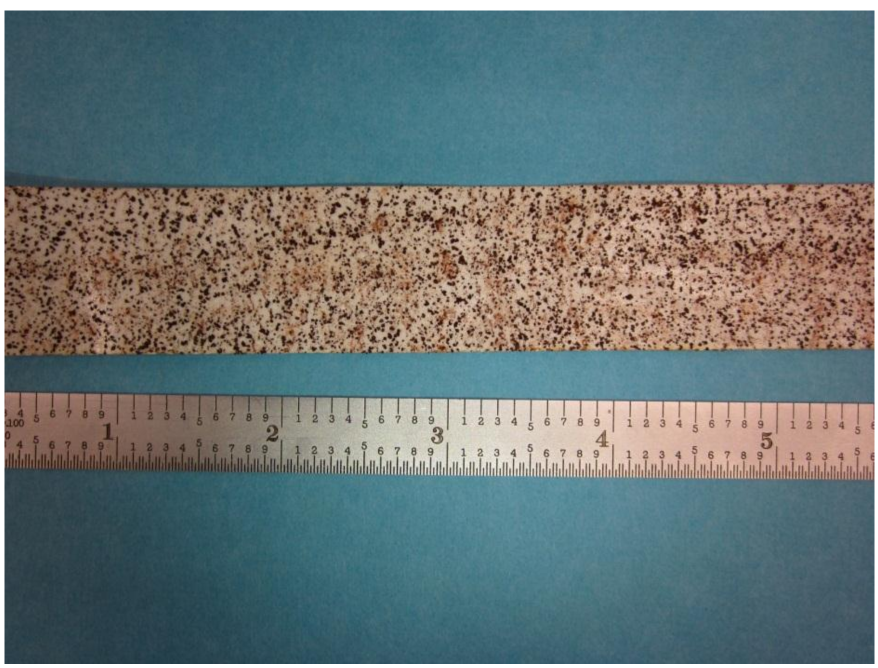

Figure 23. Category 5 tape test sample; note fine reddish rust phase particulates interspersed with more typical dark brown patina flakes.

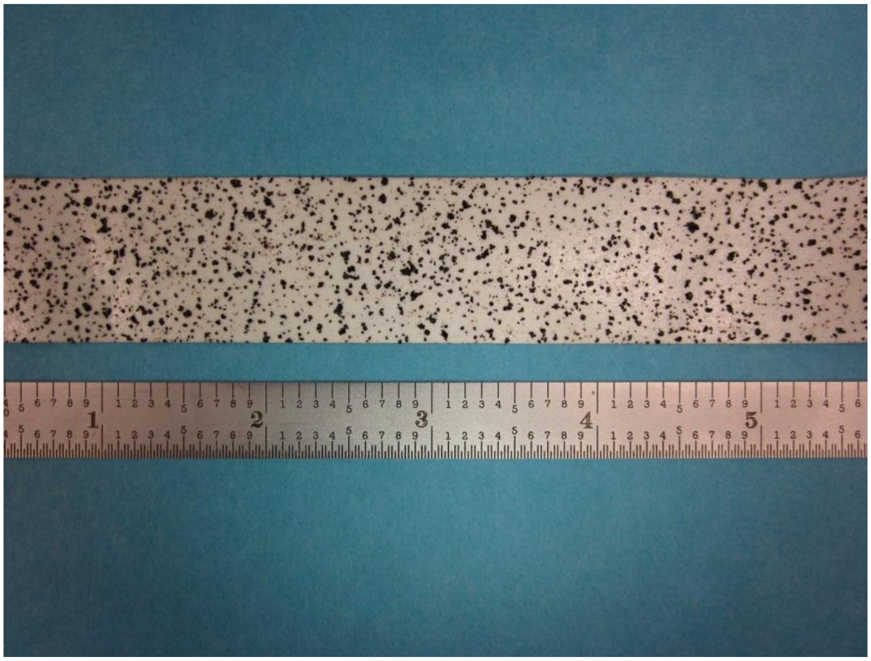

Figure 24*. Category 4 tape test sample.*

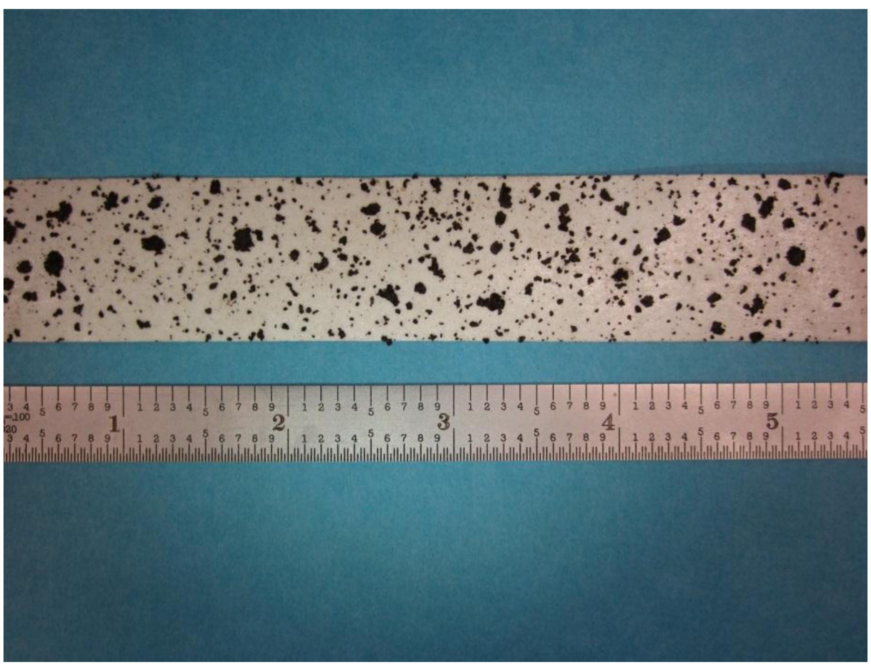

Figure 25*. Category 3 tape test sample.*

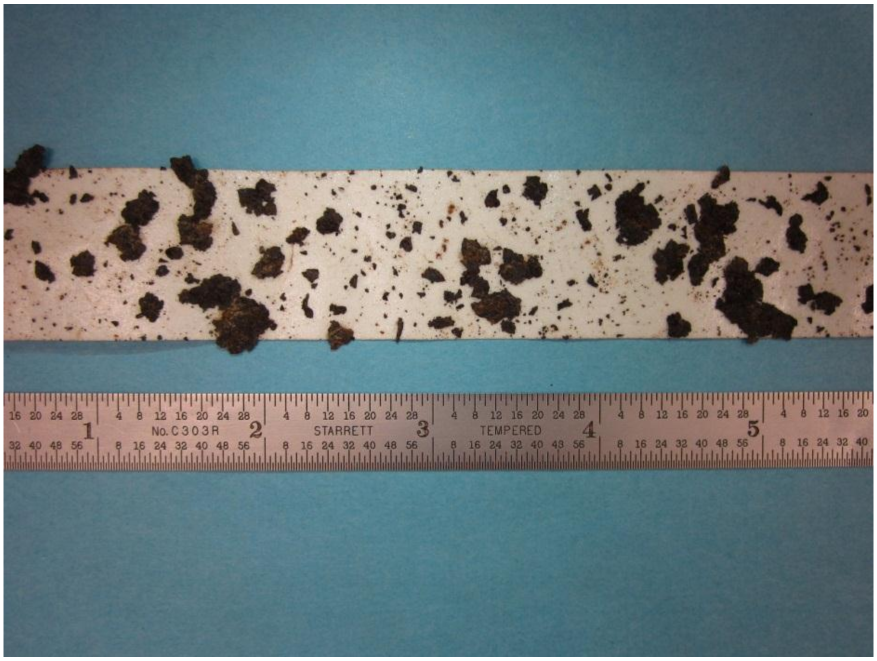

Figure 26*. Category 2 tape test sample.*

Figure 27*. Category 1 tape test sample.*

Figure 28. Fascia girder of I-235 eastbound on-ramp at 2nd Avenue. Note transition from Category 3 patina at mid-height of the web to Category 2 at the top of the bottom flange in areas subjected to direct salt spray from the I-235 mainline.

Figure 29. Overall view of I-235 eastbound mainline (left) and on-ramp at 2nd Avenue (right). Note that the portion of the on-ramp fascia girder subjected to salt spray depends on the distance from the mainline structure. As the structures come closer together, the fascia girder is shielded by the deck.

Figure 30*. CHLOR*TEST sleeve adhered to surface and being massaged during extraction.*

Figure 31*. CHLOR*TEST glass tube ready for insertion into sleeve to read results.*

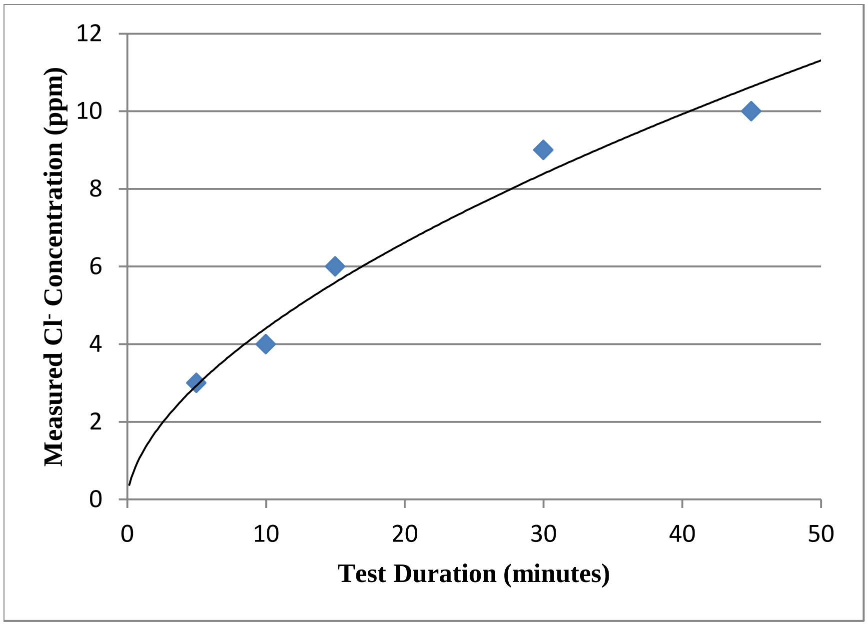

*Figure 32. CHLOR*TEST measured chloride ion concentration versus extraction time.*

Figure 33. Close-up photo of steel on top surface of girder bottom flange after wire wheel grinding at Field Selection 3; delaminated patina removed down to bare steel with oxide layer remaining in pitted areas.

Figure 34*. Pressure washing (0° nozzle) on an interior girder of Structure 0819.6R930, Field Selection 1, eastbound Iowa Route 930 over U.S. Highway 30.*

Figure 35*. Cracking with efflorescence noted in the concrete deck (arrows) at Structure 9799.5L075, Field Selection 10. Note areas of non-uniform, black weathering steel patina and salt staining on the bottom flange below each crack in the deck.*

APPENDIX A — BIBLIOGRAPHY

Appendix A — Bibliography

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APPENDIX B — INVENTORY OF WEATHERING STEEL BRIDGES IN IOWA

Table B-1. Iowa DOT Inventory of Weathering Steel Bridges

Bridge ID	NBI 008 Structure No.	Facility Carried	Features Crossed	County ID	Location	Year Built / Reconst.
0175.9R080	13101	EB I-80	IAIS RR	001 - Adair	0.5 mi. W of Jct. SR N54	2008
0175.9L080	13111	WB I-80	IAIS RR	001 - Adair	0.5 mi. W of SR N54	2009
0184.9L080	13201	WB I-80	MIDDLE RIVER	001 - Adair	1.4 mi. W. of IA 25	2011
0819.6R930	15225	EB IA 930	US 30	008 - Boone	0.6 mi. E. of SR W AVENUE	1972
1799.4L065	19011	SB US 65	WINNEBAGO RIVER	017 - Cerro Gordo	0.1 mi. North of S. jct.	2009
2500.0S210	606515	IA 210	IA 141	025 - Dallas	At Jct. of IA #141	1997
3175.5R151	608025	US 151 (NB/EB)	IA 136	031 - Dubuque	At Jct. IA 136	2002
3175.5L151	608020	US 151 (SB/WB)	IA 136	031 - Dubuque	At Jct. of IA 136	2002
3175.6R151	608140	US 151 (NB)	N FORK MAQUOKETA RIVER	031 - Dubuque	0.1 mi. N of Jct. IA 136	2002
3175.6L151	608145	US 151 (SB)	N FORK MAQUOKETA RIVER	031 - Dubuque	0.1 mi. N of Jct. IA 136	2002
4268.8R020	607855	US 20 EB	US 65	042 - Hardin	At Jct. of US 65	2003
4268.8L020	607860	US 20 WB	US 65	042 - Hardin	At Jct. of U.S. 65	2003
4278.6O020	607875	V AVENUE	US 20	042 - Hardin	2.4 mi. W of Jct. SR S56	2003
4281.0O020	607890	SR S56	US 20	042 - Hardin	At the Jct. SR S56	2003
4279.3S020	608350	US 20	IOWA RIVER	042 - Hardin	1.3 mi. W of Jct. SR S56	2003
4309.6S030	608110	US 30	UPRR	043 - Harrison	0.8 mi. E of Jct. I-29	1998
4435.8O034	608170	WINFIELD AVE	US 34/218	044 - Henry	1.5 mi. W of E Jct.US 218	2001
4442.1R218	608005	US 218 NB	US 34	044 - Henry	At S Jct. US 34	2001
4442.1L218	608010	US 218 SB	US 34	044 - Henry	At S Jct. US 34	2001
4429.1O034	608775	RAMP " C"	US 34	044 - Henry	1.6 mi. W of Jct. SR W-55	2002
4926.1S052	30091	US 52	ICE RR	049 - Jackson	2.6 mi. N of Jct. IA.#62	1996
4958.3O061	606750	SUMMIT ST	US 61	049 - Jackson	0.5 mi. S of Iowa #64	1997
4959.4L061	606480	US 61 SB	S FORK MAQUOKET RIVER	049 - Jackson	0.5 mi. N of Jct. IA #64	1998
4922.8S052	609770	US 52	ICE RR/MILL CREEK	049 - Jackson	0.3 miles south of Jct. O	2009

Table B-1. Iowa DOT Inventory of Weathering Steel Bridges (continued)

Bridge ID	NBI 008 Structure No.	Facility Carried	Features Crossed	County ID	Location	Year Built / Reconst.
5111.5O034	364895	LIBERTYVILLE RD	US 34	051 - Jefferson	1.5 mi. W. of Jct. IA #1	2006
5240.0R080	32011	EB I-80	US 6 & IAIS RR	052 - Johnson	0.9 mi. E. of Jct. I-80	1995
5243.4R080	32090	EB I-80	IOWA RIVER	052 - Johnson	3.0 mi. W. of Jct.1	1963/1998
5243.4L080	32100	WB I-80	IOWA RIVER	052 - Johnson	3.0 mi. W. of Jct.1	1963/1998
5352.9R151	607710	US 151 NB	WAPSIPINICON RIVER	053 - Jones	1.4 mi. S. of Jct. IA 64	2002
5366.4R151	608315	US 151 EB	MAQUOKETA RIVER	053 - Jones	1.0 mi. E. of Jct. IA 38	2003
5366.4L151	608320	US 151 WB	MAQUOKETA RIVER	053 - Jones	1.0 mi. E. of Jct. IA 38	2003
5604.8L027	607920	IOWA #27 SB	295TH STREET AND BNSF RR	056 - Lee	4.8 mi. N. MO St. Line	2001
5604.8R027	607925	HWY 27	295TH STREET AND BNSF RR	056 - Lee	4.8 mi. N. of MO St. Line	2001
5705.0L100	608115	IA 100	INDIAN CREEK	057 - Linn	3.2 mi. W. of Jct. US151&IA13	1995
5705.0R100	606320	EB IA 100	INDIAN CREEK	057 - Linn	3.2 mi. W. Jct. IA #13&151	1995
6266.6S063	34891	US 63	UP RR	062 - Mahaska	1.8 miles North of Jct. S	2008
6261.1O063	606720	SR G 55	US 63 & IA 163	062 - Mahaska	At W. Jct. of US #163	1996
6485.3R030	601615	EB US 30	IA 14	064 - Marshall	At Jct. IA 14	1995
6485.3L030	601620	WB US 30	IA 14	064 - Marshall	At Jct. IA 14	1995
7251.6O060	364700	SR A22	IA 60	072 - Osceola	1.9 mi. S. of Jct. Iowa #9	2006
7248.9O060	504615	2ND AVENUE	IA 60	072 - Osceola	4.6 mi. S. of Jct. IA #9	2006
7250.3O060	609635	SEC. ROAD L-40	IA 60	072 - Osceola	3.2 mi. S. of Jct. Iowa #9	2006
7710.3A235	608630	UNIVSITY RAMP A	UPRR	077 - Polk	0.2 mi. E. of Jct. IA #163	2001
7710.3L235	42961	WB I-235	UP RR	077 - Polk	0.2 mi. E. of Jct. IA 163	2004
7710.3R235	42951	EB I-235	RR	077 - Polk	0.2 mi. E. of Jct. IA 163	2004
7724.1O080	12491	W UNIVERSITY	I-35 & I-80	077 - Polk	0.1 mi. E. of W Jct. I-35	1984/2004

Table B-1. Iowa DOT Inventory of Weathering Steel Bridges (continued)

Bridge ID	NBI 008 Structure No.	Facility Carried	Features Crossed	County ID	Location	Year Built / Reconst.
7774.0R065	606775	NB US 65	AVON RD	077 - Polk	1.0 mi. N. of N Jct. IA.#5	1997
7774.0L065	606780	SB US 65	AVON RD	077 - Polk	1.0 mi. N. of Jct. IA #5	1997
7778.1R065	606825	U.S. 65 NB	S.E. 6TH AVE	077 - Polk	1.3 mi. S. of Jct. IA #163	1997
7778.1L065	606830	U.S. 65 SB	S.E. 6TH AVE	077 - Polk	1.3 mi. S. of Jct. IA #163	1997
7773.0L065	606760	SB US 65	RELOC IA 5	077 - Polk	At N Jct. of IA #5	1997
7773.0R065	606755	NB US 65	RELOC IA 5	077 - Polk	At N Jct. of IA #5	1997
7731.5R080	41441	NB I-35/EB I-80	IA 28	077 - Polk	At Jct. IA 28	1999
7731.5L080	41451	SB I-35,WB I-80	IA 28	077 - Polk	At Jct. IA 28	1999
7735.5R080	41591	NB I-35,EB I-80	IA 415	077 - Polk	At Jct. of IA 415	1999
7735.5L080	41601	I-80 WB/I-35 SB	IA 415	077 - Polk	At Jct. of IA 415	1999
7736.5R080	41631	NB I-35,EB I-80	US 69	077 - Polk	At Jct. US 69	2000
7736.5L080	41641	SB I-35,WB I-80	US 69	077 - Polk	At Jct. U.S. 69	2000
7726.1O080	41331	DOUGLAS AVE	I-35 AND I-80	077 - Polk	1.0 Mile North Of US#6	2002
7738.9S006	504520	US 6	I-235	077 - Polk	At Jct. I-235	2003
7709.5R235	42891	EB I-235	NB U.S. 69/E 15TH ST.	077 - Polk	At the Jct. U.S. 69	2004
7785.5S069	40521	E 14TH ST-US 69	I-235	077 - Polk	At the Jct. I-235	2003
7709.1O235	42871	SE 12TH ST	I-235	077 - Polk	5.2 mi. E. of Jct. IA #28	2002
7709.0O235	4111	E. 9TH STREET	I-235	077 - Polk	5.1 mi. E. of Jct. IA #28	2001
7708.9O235	42841	PENN AVE	I-235	077 - Polk	5.0 mi. E. of Jct. IA #28	2002
7708.8O235	608680	E 6TH ST	I-235	077 - Polk	4.9 mi. E. of Jct. IA #28	2002
7708.5S235	42740	I-235	DES MOINES RIVER AND RD	077 - Polk	4.6 mi. E. of Jct. IA #28	1962/2007
7708.5A235	42761	2ND AVE EB RAMP	WEST RIVER DRIVE	077 - Polk	4.6 mi. E. of Jct. IA #28	2003
7708.3O235	42731	2ND AVE	I-235	077 - Polk	4.4 mi. E. of Jct. IA #28	2003
7708.3A235	42721	RAMP	S-W CONN OVER WB I-235	077 - Polk	4.4 mi. E. of Jct. IA #28	2002
7708.2O235	42711	3RD ST	I-235	077 - Polk	4.3 mi. E. of Jct. IA #28	2003

Table B-1. Iowa DOT Inventory of Weathering Steel Bridges (continued)

Bridge ID	NBI 008 Structure No.	Facility Carried	Features Crossed	County ID	Location	Year Built / Reconst.
7708.1O235	608950	5TH AVE	I-235	077 - Polk	4.2 mi. E. of Jct. IA #28	2003
7708.0O235	42621	6TH AVE	I-235	077 - Polk	4.1 mi. E. of Jct. IA #28	2004
7707.9O235	42611	7TH ST	I-235/3RD ST. RAMP B	077 - Polk	4.0 mi. E. of Jct. IA #28	2003
7707.8O235	42571	9TH STREET	I-235	077 - Polk	3.9 mi. E. of Jct. IA #28	2007
7789.1O035	609280	CORP WOODS DR	I-35	077 - Polk	1.9 mi. N. of Jct. I-80/2	2003
7707.2O235	42491	W 19TH ST	I-235	077 - Polk	3.3 mi. E. of Jct. IA #28	2003
7706.9O235	42431	COTTAGE GROVE	COTTAGE GROVE	077 - Polk	3.0 mi. E. of Jct. IA #28	2003
7707.1O235	608565	M. LUTHER KING	I-235	077 - Polk	3.2 mi. E. of Jct. IA #28	2003
7710.1L235	609260	WB I-235	IA #163/UNIV. AVE/RAMP	077 - Polk	0.6 mi. E. of Jct. US 69 NB	2004
7710.5R235	609395	I-235 EB	EASTON BLVD	077 - Polk	0.4 mi. E. of Jct. IA #163	2004
7710.0A235	609365	UNI AVE WB ENTR	WB EXIT RAMP, UNIV. AVE.	077 - Polk	0.5 mi. E. of Jct. U.S. 69	2004
7707.5A235	504625	19TH ST RAMP	KEO WAY	077 - Polk	3.6 mi. E. of Jct. IA #28	2004
7709.9A235	609255	E 15TH RAMP D	E UNIVERSITY RAMP B	077 - Polk	0.3 mi. E. of Jct. U.S. 69	2004
7709.5L235	601356	WB I-235	15TH STREET	077 - Polk	At the Jct. U.S. 69	2005
7707.5L235	42521	WB I-235	KEO WAY	077 - Polk	3.6 mi. E. of Jct. IA #28	2005
7710.1R235	42921	EB I-235	UNIVERSITY AVE	077 - Polk	0.6 mi. E. of Jct. US 69 NB	2005
7704.4O235	42321	56TH ST	I-235	077 - Polk	0.5 mi. E. of Jct. IA #28	2005
7708.1A235	42641	S-E CONN TO 3RD	I-235 EB RAMP	077 - Polk	4.2 mi. E. of Jct. IA #28	2005
7707.7A235	609695	EB I-235 RAMP	KEO WAY RAMP TO EB I-235	077 - Polk	3.8 mi. E. of Jct. IA #28	2005
7710.5L235	608570	I-235 WB	EASTON BLVD	077 - Polk	0.4 mi. E. of Jct. IA #163	2006
7707.5R235	42511	EB I-235	KEO WAY	077 - Polk	3.6 mi. E. of Jct. IA #28	2006
7743.7O080	42061	CO RD S14	I-80	077 - Polk	1.7 Miles E of Hwy #65/NE	2006
7713.8R235	609860	EB I-235	NB I-35 & EB I-80	077 - Polk	At the E Jct. I-35/80	2007
7713.9R235	609865	EB I-235	WB I-235 & WB I-80	077 - Polk	At the E Jct. I-35/80	2007

Table B-1. Iowa DOT Inventory of Weathering Steel Bridges (continued)

Bridge ID	NBI 008 Structure No.	Facility Carried	Features Crossed	County ID	Location	Year Built / Reconst.
7713.8L235	609810	WB I-235	NB I-35 & EB I-80	077 - Polk	At the E Jct. I-35/80	2007
7713.9L235	609815	WB I-235	WB I-235 & WB I-80	077 - Polk	At the E Jct. I-35/80	2007
7713.8A235	609935	EBI235 TO WBI80	EB I-80	077 - Polk	At I-35/80/235 interchange	2008
7713.9A235	609945	EBI235 TO WBI80	WB I-80	077 - Polk	At East Mixmaster	2009
7787.1S035	609940	EBI80 TO NBI35	WB I-80	077 - Polk	At the N Jct. I-80/I-235	2009
7787.0A035	700000	SBI35 TO EBI80	NB I-35 & EB I-80	077 - Polk	At East Mixmaster	2009
7713.8S235	700005	WBI80 TO WBI235	NB I-35 & EB I-80	077 - Polk	At East Mix Master	2009
7787.1A035	609995	SBI35 TO EBI80	WB I-80	077 - Polk	At East Mixmaster	2009
7709.9R163	40970	EB IA 163	MUD CREEK	077 - Polk	2.2 mi. W. of Jct.316	1963/2008
7709.9L163	40980	WB IA 163	MUD CREEK	077 - Polk	2.2 mi. W. of Jct.316	1963/2008
7768.5R035	41141	NB I-35	RACOON RIVER	077 - Polk	0.6 mi. N of Jct. Iowa #5	2002
7768.5L035	41151	SB I-35	RACOON RIVER	077 - Polk	0.6 mi. N of Jct. Iowa #5	2003
7712.2R163	40991	EB IA 163	CAMP CREEK	077 - Polk	0.1 mi. E. of Jct. 316	2007
7712.2L163	41001	WB IA 163	CAMP CREEK	077 - Polk	0.1 mi. E. of Jct. 316	2007
7801.7O080	44691	24TH ST	I-80	078 - Pottawattamie	1.7 mi. E of Neb. St. Line	2008
7802.4R080	44680	SB I-29,EB I-80	INDIAN CREEK	078 - Pottawattamie	2.4 mi. E. of Neb. St. Line	1968
7866.6R029	44941	NB I-29	HONEY CREEK	078 - Pottawattamie	4.4 mi. S. of N Jct. I-680	2009
7866.6L029	44951	SB I-29	HONEY CREEK	078 - Pottawattamie	4.4 mi. S. of N Jct. I-680	2009
7814.2S006	43231	US 6	KEG CREEK	078 - Pottawattamie	0.4 mi. E of S.R. L52	2011
7839.5R080	45531	EB I-80	WEST NISHNABOTNA RIVER	078 - Pottawattamie	0.8 mi. W. of Jct.59	2011
8903.8S001	50181	IOWA #1	DES MOINES RIVER	089 - Van Buren	3.8 mi. N. of Jct. IA #2	2007
9039.1R063	609115	RELOC US 63 NB	ICE RR	090 - Wapello	1.6 mi. S. of Jct. IA #149	2007
9039.1L063	609120	RELOC US 63 SB	ICE RR	090 - Wapello	1.6 mi. S. of Jct. IA #149	2007
9038.3O063	609125	120TH AVENUE	US 63	090 - Wapello	2.3 mi. S. of Jct. IA #149	2005
9193.2R005	601935	NB IA 5	US 69	091 - Warren	At Jct. of US 65 & US 69	1997/2000
9193.2L005	601770	SB IA 5/US 65	NB 69-SB69-SB65	091 - Warren	At W. Jct. Of US#65/69	1997

Table B-1. Iowa DOT Inventory of Weathering Steel Bridges (continued)

Bridge ID	NBI 008 Structure No.	Facility Carried	Features Crossed	County ID	Location	Year Built / Reconst.
9197.7O005	607220	ECHO VALLEY DR.	IA 5	091 - Warren	1.4 mi. S of IA #28	2000
9196.0L005	607280	SB IA 5	SR R63 (SW 9TH)	091 - Warren	2.9 mi. W of Jct. US 69	2000
9196.0R005	607285	NB IA 5	SR R63 (SW 9TH)	091 - Warren	2.9 mi. N Jct. US 69	2000
9187.5L005	606920	SB/EB IA 5	MIDDLE RIVER	091 - Warren	1.4 mi. S of SR G-16	1997
9180.5L005	50995	IA 5 SB	SOUTH RIVER	091 - Warren	0.2 mi. N of Jct. SR S31	2000
9154.4R035	51301	NB I-35	CLANTON CREEK	091 - Warren	2.4 mi. S of Jct. IA #92	2007
9154.4L035	51311	SB I-35	CLANTON CREEK	091 - Warren	2.4 mi. S of Jct. IA #92	2007
9145.4R035	51221	NB I-35	SOUTH RIVER	091 - Warren	On I-35 over South River	2011
9280.9R218	605593	NB US 218	IA 22	092 - Washington	At Jct. IA #22 & US #218	1995
9416.7L020	609710	US 20 WB	SR D20 & UP RR	094 - Webster	0.5 mi. E. of Jct. Webster	2008
9458.9R169	52211	NB US 169	LIZARD CREEK	094 - Webster	0.3 mi. S. of IA 7	2010
9799.5R075	607985	US 75 (NB)	BUS 75	097 - Woodbury	5.8 mi. N Jct. Iowa #12	1999
9799.5L075	607980	US 75 (SB)	RAILROAD & RAMP	097 - Woodbury	5.8 mi. N Jct. IA 12	1999
9718.0L020	52931	WB US 20	W.FORK LITTLE SIOUX RIVER	097 - Woodbury	0.1 mi. W of Jct. IA 140	2004
9712.1L020	52901	WB US 20	ELLIOT CREEK	097 - Woodbury	6.0 mi. W of Jct. IA 140	2006
9705.2S141	53241	IA 141	DRAINAGE DITCH	097 - Woodbury	2.0 mi. W. of SR K-64	2010
9811.3O035	600200	FM RD A-34	I-35	098 - Worth	7.3 mi. N. of IA #9	1970
9951.4O035	602615	FM R-75	I-35	099 - Wright	At Jct. R-75	1971

APPENDIX C — FIELD SHEET SUMMARIES

Table C-1. List of Bridges Selected for the Iowa Field Investigation

Field Selection No.	Structure Name	Bridge ID	County	Year Built
1*	EB IA-930 over US-30	0819.6R930	Boone	1972
2	US-151 over IA-36	3175.5R151	Dubuque	2002
		3175.5L151	Dubuque	2002
	US-151 over the N. Fork Maquoketa River	3175.6R151	Dubuque	2002
		3175.6L151	Dubuque	2002
3	US-30 over IA-14	6485.3R030	Marshall	1995
		6485.3L030	Marshall	1995
4	US-65 over Avon Road	7774.0R065	Polk	1997
		7774.0L065	Polk	1997
5	I-35 and I-80 over IA-28	7731.5R080	Polk	1999
		7731.5L080	Polk	1999
6	Douglas Avenue over I-35 and I-80	7726.1O080	Polk	2002
7	E. 14th Street (US-69) over I-235	7785.5S069	Polk	2003
	E. 12th Street over I-235	7709.1O235	Polk	2002
	E. 9th Street over I-235	7709.0O235	Polk	2001
	Pennsylvania Avenue over I-235	7708.9O235	Polk	2002
	E. 6th Street over I-235	7708.8O235	Polk	2002
	I-235 over the Des Moines River and the I-235 E.B. Entrance Ramp at 2nd Avenue	7708.5S235	Polk	2007
		7708.5A235	Polk	2003
	2nd Avenue over I-235	7708.3O235	Polk	2003
	2nd Avenue Ramp over I-235	7708.3A235	Polk	2002
	3rd Street over I-235	7708.2O235	Polk	2003
	5th Avenue over I-235	7708.1O235	Polk	2003
	6th Avenue over I-235	7708.0O235	Polk	2004
	7th Street over I-235	7707.9O235	Polk	2003
8	I-80EB and I-29SB over Indian Creek	7802.4R080	Pottawattamie	**
9	US-218 over IA-22	9280.9R218	Washington	1995
10	US-75 over Bus-75 and Railroad	9799.5R075	Woodbury	1999
		9799.5L075	Woodbury	1999
11	FM RD A-34 over I-35	9811.3O035	Worth	1970
12*	FM R-75 over I-35	9951.4O035	Wright	1971

*Included in the AISI study during the early 1990’s
**Bridge constructed with painted steel in 1968 and widened with weathering steel at later time, date unknown.

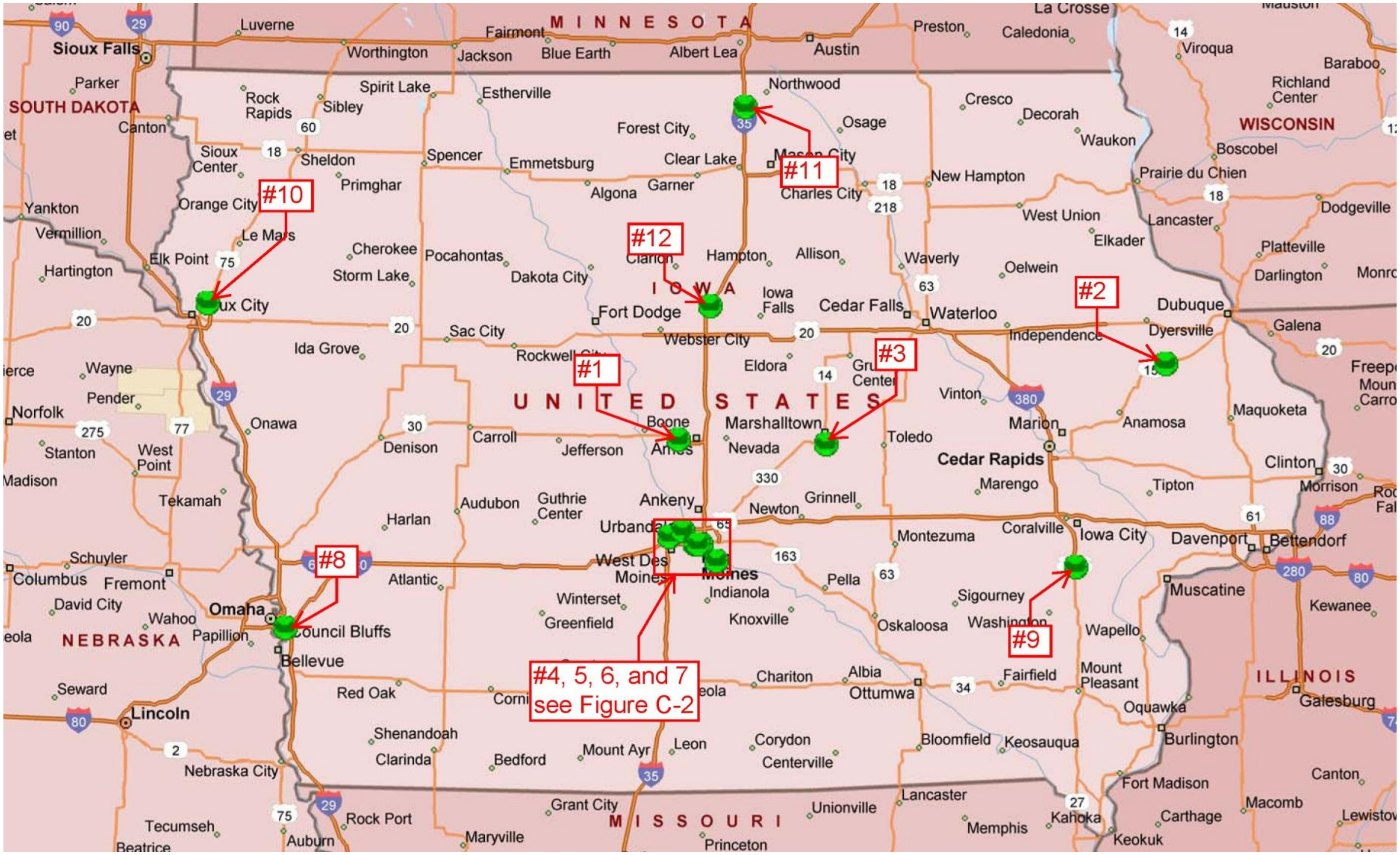

Figure C-1. Map showing locations of weathering steel bridges selected for the Iowa field investigation (Field Selection number shown, refer to Table C-1).

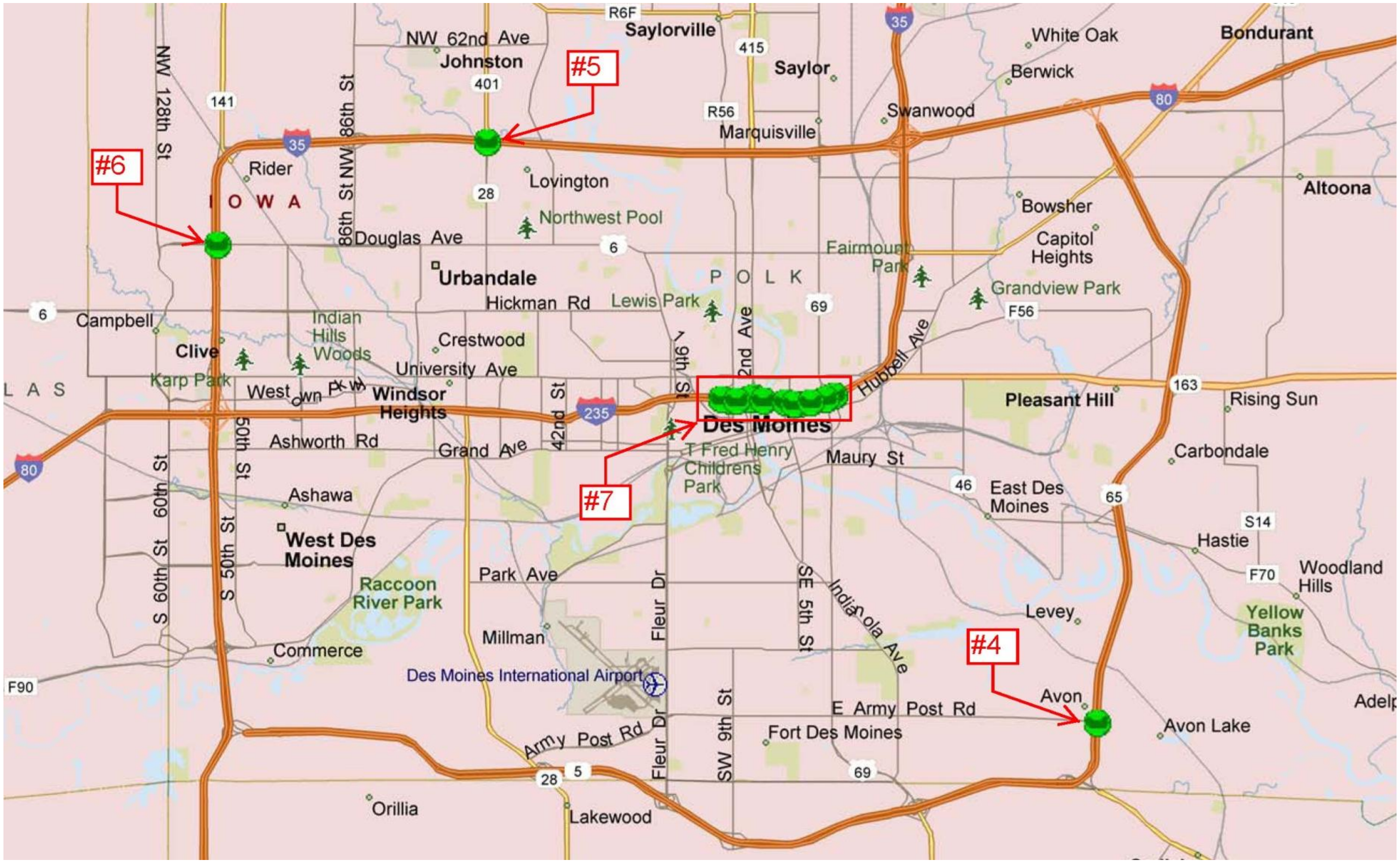

Figure C-2. Des Moines area map showing locations of weathering steel bridge investigations (Field Selection number shown, refer to Table C-1 and Figure C-1).

EB IA-930 over US-30 — 0819.6R930

NBI Structure No. 15225

MAP ID: 1	
FACILITY CARRIED: IA-930 EB	
FEATURES CROSSED: US-30	
COUNTY: 008 - Boone	
LOCATION: 0.6 Miles East of SR W Avenue	
LATITUDE: 42.0226703	
LONGITUDE: -93.72616699	
YEAR BUILT: 1972	
VERTICAL UNDER CLEARANCE: 17'-11"	
AADT UNDER (ESTIMATED): 14,600	
% TRUCKS UNDER (ESTIMATED): 8%	

STRUCTURE DESCRIPTION:

Five continuous girders, four span conventional abutment bridge with an approximate 30° skew. Wide flange diaphragms at abutments, typical cross-frames are single angle diagonals and WT bottom members. Outside bays have WT lateral bracing for the full length of the two interior spans; there is no lateral bracing in abutment spans.

SUMMARY OF CONDITION:

- Patina index is 3 on average, with exterior fascia surfaces typically 3.5 to 4 and interior trouble zones 2.5 to 2. Sides of members facing traffic appear slightly worse (about 0.5 index points) than those facing away; this difference disappears away from traffic near abutments. Overall, good performance after 40 years of service.
- Patina seems to be about a half a point worse closer to the south abutment on the south half of the bridge and near the center pier on the north half of the bridge; perhaps due to superelevation of U.S. 30 causing majority of deicing salts to drain to the south half of each roadway and be splashed up on the bridge there.
- Bridge deck concrete is deteriorating, with spalling, cracking, and some previous repairs. At isolated locations, leakage through deck causing rapid corrosion (possibly index = 1) of girder top flanges.

TESTING PERFORMED:

- Tape test profiles of fascia and center girders near north abutment; comparative tape tests on webs over traffic lanes (toward and away) on south half of bridge.
- Chloride and tape testing of diaphragm web at north abutment expansion joint; only minor difference in patina condition (Index = 3.5 to 3) from front to back side and chlorides measured between 0 and 2 ppm.
- Washing of two interior girders with 40° and 0° nozzles, along with varying surface preparation techniques. Tape and chloride tests taken before and after show 0° nozzle more effective and significant salts trapped beneath patina surface, particularly on older bridges.

Figure 1. North roadway span showing bracing arrangement and spall locations in the deck.

Figure 2. Top flange deterioration beneath concrete deck crack; possibly index rating of 1 on hidden top.

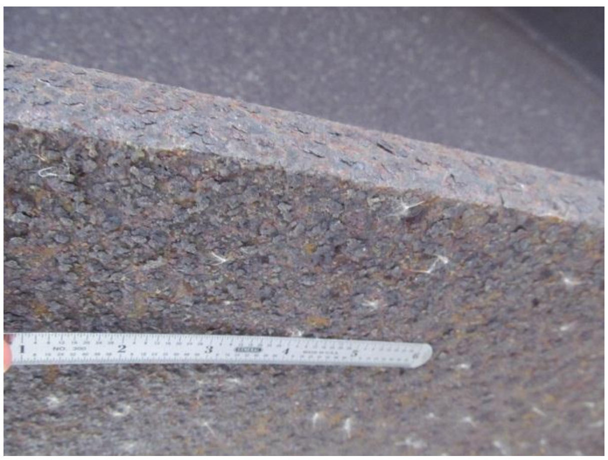

Figure 3. Flakiness on interior bottom flange near south abutment (Index = 2.5). Worse than over traffic on north half of bridge.

Figure 4. Interior bottom flange condition near north abutment; index here is 3.5. Contrast with Figure 3 from identical location at south end.

Figure 5. Excellent patina performance on exterior fascia faces after 40 years, typical of rural bridges.

Figure 6. Non-flaky poultice over traffic, typical of narrow rural bridges.

US-151 over Iowa Route 136	**3175.5L151 and 3175.5R151**
NBI Structure No. 608020 and 608025	
	MAP ID: 2
	FACILITY CARRIED: US-151 NB and SB
	FEATURES CROSSED: IA-136
	COUNTY: 031 - Dubuque
	LOCATION: Jct. IA 136
	LATITUDE: 42.305184
	LONGITUDE: -91.022999
	YEAR BUILT: 2002
	VERTICAL UNDER CLEARANCE: 17'-1"
	AADT UNDER (ESTIMATED): 2,000
	% TRUCKS UNDER (ESTIMATED): 20%

STRUCTURE DESCRIPTION:

Side-by-side integral abutment, single span bridges similarly constructed with varying width and slight skews. The northbound bridge (608025) has six girders, while the southbound structure (608020) has eight. Typical cross-frames are single angle diagonals with WT bottom members. Sufficient clear distance separates the bridges to prevent direct snow/salt spray from the adjacent bridge. Bridges slope toward the north abutment. Minimal substructure staining at north ends.

SUMMARY OF CONDITION:

- Patina generally performing well, with both bridges having similar conditions. Average patina index rating is 3.5, with some areas approaching 3. Uniform dark brown coloration.
- Minimal poultice corrosion noted, even on interior bottom flanges.
- Northbound bridge has localized areas of discoloration indicative of incomplete patina formation possibly due to mill scale or surface contamination during construction.
- Light traffic and the relatively young age of this bridge likely contributing to its good performance to date.

TESTING PERFORMED:

- Visual inspection from abutment slopewalls and via aerial lift.
- Tape, chloride, and color tests taken on west fascia girder of southbound bridge over eastbound IA-136 shoulder. No meaningful color data.
    - Patina slightly worse on exterior top of bottom flange than exterior web (Index 3 vs. 4) with chlorides measured in the range of 2 to 4 ppm.
    - Tape test profile of all exterior and interior surfaces revealed Index range from 4 to 3, with the bottom flange surfaces having the largest flakes.

Figure 1. Patina discoloration on west fascia of northbound bridge, possibly due to mill scale (Index = 5 locally in these areas).

Figure 2. Typical conditions underneath interior of both bridges. Index = 3.5 to 3 on bottom flanges. Sound deck prevents water infiltration from above.

Figure 3. Index 4 and 3 patina on web and top of bottom flange, respectively, near fascia girder tape and chloride tests on 608020.

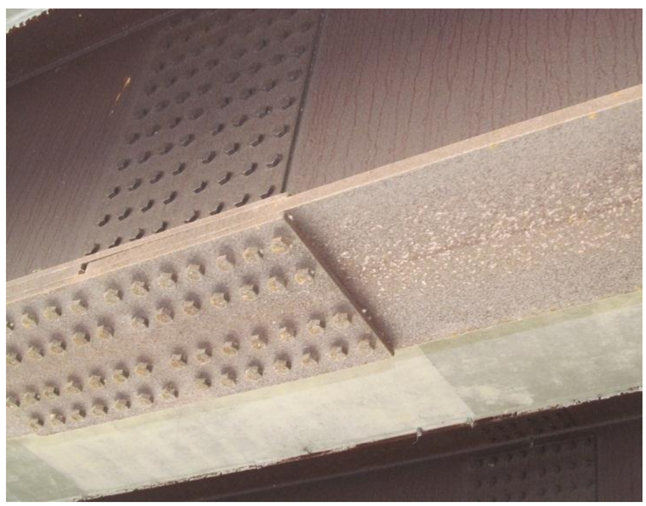

Figure 4, Mild salty staining and flakiness visible on bottom flange near girder splices over shoulder. Patina Index = 3.

US-151 over the North Fork Maquoketa River 3175.6R151 and 3175.6L151

NBI Structure No. 608140 and 608145

MAP ID: 2

FACILITY CARRIED: US-151 NB and SB

FEATURES CROSSED: North Fork Maquoketa River

COUNTY: 031 - Dubuque

LOCATION: 0.1 mi. N of Jct. IA 136

LATITUDE: 42.30622838

LONGITUDE: -91.02157834

YEAR BUILT: 2002

VERTICAL UNDER CLEARANCE: N/A

AADT UNDER (ESTIMATED): N/A

% TRUCKS UNDER (ESTIMATED): N/A

STRUCTURE DESCRIPTION:

Two bridges similarly constructed with five continuous girders each, with one additional girder originating within a span to allow for a widening of each bridge as it approaches its south abutment. Each bridge has five spans, conventional stub abutments, and channel diaphragms at the abutments. Typical cross-frames are single angle diagonals with WT bottom members. 608140 carries the northbound lanes and 608145 carries southbound traffic. Approximately 60 feet of clear distance separates the bridges.

SUMMARY OF CONDITION:

- Patina generally performing well, with both bridges having similar conditions. Average patina index rating is 4, with only a few areas approaching 3. Uniform dark brown coloration.
- Very localized index 2 at bottom of fascia bottom flange and bottom of web near the south abutment.
- Minimal poultice corrosion noted, even on interior bottom flanges.
- Evidence of deterioration on fascia exterior surfaces (top and bottom of bottom flange) adjacent to short downspout nearest south abutment. Likely due to drain splash and spray onto girder, both direct via wind and also indirect off rock apron. Accounts for index 2 tape test on bottom of flange at this location. Deterioration spreads down the girder slope from the drain for some distance before dissipating.

TESTING PERFORMED:

- Visual inspection limited to foot access only since no access road was available.
- Tape, chloride, and color tests taken on exterior and interior surfaces near south abutment; typically little patina variation (Index 4 to 3.5), chlorides measured at 1 ppm or less. No meaningful color data.
- Tape test on west fascia near drain reveals moderate flaking on the bottom of the flange (Index = 2).

Figure 1. West fascia near south abutment, showing short downspout, painted girder end, and rock apron.

Figure 2. South abutment, showing typical cross-frames and diaphragms detailed to not stain concrete.

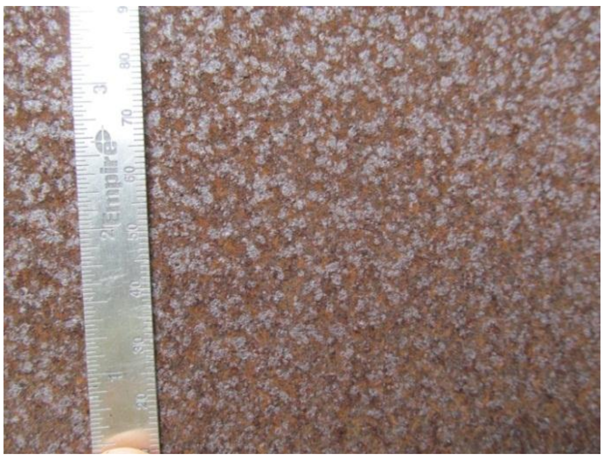

Figure 3. Typical close-up of Index 4 patina on fascia web.

Figure 4, Larger flakes on bottom of fascia bottom flange near downspout by south abutment.

Figure 5. Tape test series taken from west fascia girder adjacent to downspout showing large flakes (Index=2) on bottom of bottom flange.

Figure 6. View of downspout; bottom flange corrosion extends away from spout, primarily in direction of girder slope.

US-30 over IA-14 — 6485.3R030 and 6485.3L030

NBI Structure No. 601615 and 601620

MAP ID: 3

FACILITY CARRIED: US-30

FEATURES CROSSED: IA-14

COUNTY: 064 - Marshall

LOCATION: At JCT. IA-14

LATITUDE: 42.00381636

LONGITUDE: -92.91240179

YEAR BUILT: 1995

VERTICAL UNDER CLEARANCE: 17’-1”

AADT UNDER (ESTIMATED): 3,400

% TRUCKS UNDER (ESTIMATED): 6%

STRUCTURE DESCRIPTION:

Both bridges have five continuous plate girders over three spans, with conventional abutments and no skew. Cross-frames between girders are single angle diagonals with a WT bottom member; wide flange diaphragms at the abutments. Drainage deflector plates only installed on exterior fascia flanges; water may migrate on interior from span to span (all spans slope west slightly). Evidence of expansion joint leaking, but steel painted near these joints and coatings in apparent good condition. Clear distance from 601620 (westbound) to 601615 (eastbound) is about 50 feet. IA-14 crown is in center of road; water beneath drains to both sides of center span.

SUMMARY OF CONDITION:

- Average patina condition index ratings are 3.5 to 4 for exterior surfaces, 3 on vertical interior surfaces, and 2 or worse on horizontal interior surfaces in both center and abutment spans.
- Patina condition better on average (0.5 to 1 index points) on all surfaces on west half of bridge than east half. Bottom flange poultice a bit more pronounced, but with less flakiness. Perhaps due to IA-14 traffic light north of bridges and U.S. 30 on-ramps resulting in slower southbound traffic on average than incoming rural northbound traffic (and more spray accordingly).
- Patina conditions virtually identical on both bridges; no signs of interaction on fascia girders due to snow/salt spray from adjacent bridge.

TESTING PERFORMED:

- Interior girder tape and chloride tests near east abutment of eastbound bridge.
- Pressure washing (0° nozzle) of interior girder and cross-frame over northbound shoulder of eastbound bridge, both with water and CHLOR*RID solution. Various surface preparations made (e.g. wire brush, wire wheel grinding).
  - CHLOR*RID provided virtually identical chloride reduction results to washing with water alone.
  - 0° nozzle washing at 3500 psi removed the loose rust layer down to an adherent surface, though not fully on top of bottom flanges with heavy poultice. These may require higher wash pressures.
  - Significant chlorides remained on wire wheel ground areas after washing, providing continued evidence of trapped chlorides deep in pits and beneath the patina.

Figure 1. Top of bottom flange poultice prior to washing; Index = 2, chlorides measured = 20 ppm.

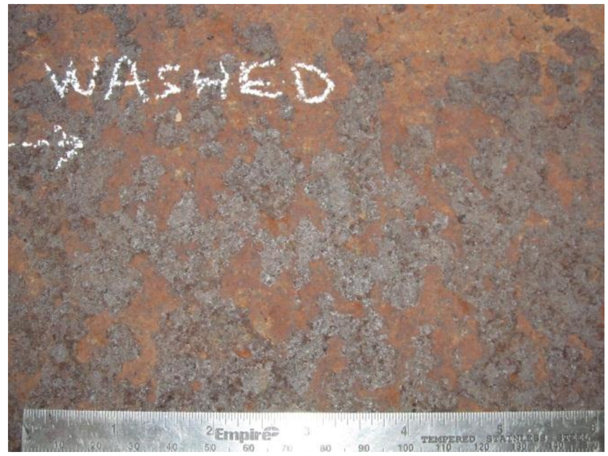

Figure 2. Top of bottom flange after washing; some of poultice remains, Index = 2, chlorides = 10 ppm.

Figure 3. Top of bottom flange ground with wire wheel. Chlorides in ground area before washing = 20 ppm; after washing, 14 ppm extracted by test.

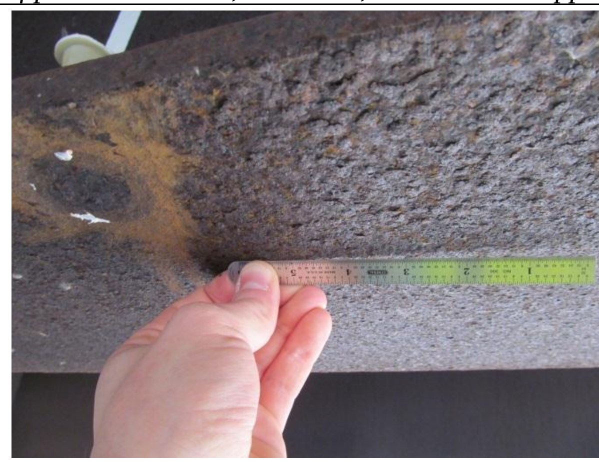

Figure 4. Flaking on bottom of flange near east abutment of 601615; Index = 2. Chlorides at this location measured at 14 ppm.

Figure 5. Bottom of flange near west abutment shows less flaking than east side; Index = 3.

Figure 6. Bottom of web after washing; tape test (sparse, Index = 3) shows improvement in adherence (Index before = 2 with dense coverage).

US-65 over Army Post Road — 7774.0R065 and 7774.0L065

NBI Structure No. 606775 and 606780

MAP ID:	4
FACILITY CARRIED:	US-65 NB
FEATURES CROSSED:	Avon Road, Army Post Road
COUNTY:	077- Polk
LOCATION:	1.0 Miles North of N JCT. IA. #5
LATITUDE:	41.52487503
LONGITUDE:	-93.51943909
YEAR BUILT:	1997
VERTICAL UNDER CLEARANCE:	17’-2”
AADT UNDER (ESTIMATED):	8,700
% TRUCKS UNDER (ESTIMATED):	

STRUCTURE DESCRIPTION:

Side-by-side three span continuous girder bridges with conventional abutments and sloped abutment embankments. Northbound US 65 (606775) has six girders, southbound U.S. 65 (606780) has five girders. Cross frames between girders are single angle diagonals with WT bottom members; channel diaphragms present at the girder ends. Diaphragms and girder ends are painted; minor rust staining of piers. Conditions similar on both structures, no signs of interaction on fascia girders due to snow/salt spray from adjacent bridge.

SUMMARY OF CONDITION:

- Patina condition index averages 3.5, with some areas of 3 or localized 2, particularly on tops and bottoms of bottom flanges, and also at girder splices. Fascia girder webs rate at index = 4.
- Coloration is uniform dark brown, with some moderate chalking of interior bottom flanges. Poultice seems heavier on south end of girders than north, perhaps because two spans drain to the south, while the north span drains toward the north abutment. Localized discoloration noted on one interior web, perhaps due to mill scale.
- After 15 years, localized deterioration beginning to develop despite relatively favorable suburban environment.

TESTING PERFORMED:

- Color, chloride, and tape tests on fascia and interior surfaces both near south abutment and over traffic.
  - Chlorides ranged from 0 ppm on web away from traffic to 50 ppm on girder flange over lane.
  - Color testing showed significant variation between poultice and normal patina coloration on web.
- Core sample taken from cross-frame over traffic; washing (40º nozzle) conducted on interior girder.
  - Top of bottom flange chlorides reduced from 50 ppm to 25 ppm by washing, but tape test results virtually identical (Index = 3.5).
  - Chlorides next to core were 30 ppm (due to poultice) on top of WT stem and 2 ppm below.

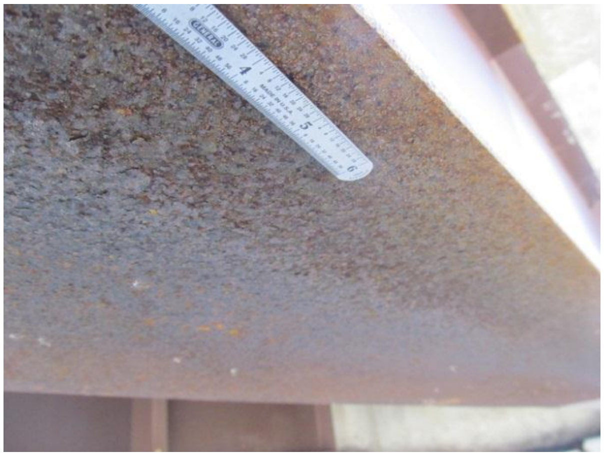

Figure 1. Flakiness of bottom flange near south abutment (Index = 2.5).

Figure 2. Fascia girder exterior web patina over traffic (Index = 4). Note darker band above weld.

Figure 3. Interior girder over traffic showing poultice with minimal flaking and reddish web discoloration, possibly due to mill scale.

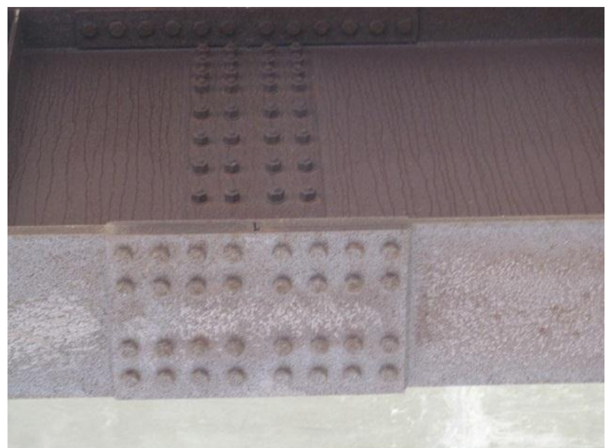

Figure 4. Flaking on and around girder splice.

Figure 5. Poultice on flange before washing.

Figure 6. Flange poultice partially reduced by washing.

I-35 and I-80 over IA-28	**7731.5R080 and 7731.5L080**
NBI Structure No. 41441 and 41451	
	MAP ID: 5
	FACILITY CARRIED: I-35 and I-80
	FEATURES CROSSED: IA-28
	COUNTY: 077- Polk
	LOCATION: at Junction IA-28
	LATITUDE: 41.6521151
	LONGITUDE: -93.69766796
	YEAR BUILT: 1999
	VERTICAL UNDER CLEARANCE: 17'-3"
	AADT UNDER (ESTIMATED): 29,800
	% TRUCKS UNDER (ESTIMATED):

STRUCTURE DESCRIPTION:

Sixteen continuous girders, two spans. Built in five stages. Integral abutments, sloped abutment embankments. Cross frames between girders are single angle diagonals with WT bottom members. Built as two separate structures, with a 2 inch gap between but shared substructure elements (41441 is south structure, 41451 is north). Similar geometry to Douglas Ave. Bridge (7726.1O080, Map ID 6), but in a different environment.

SUMMARY OF CONDITION:

- Patina condition index = 3.5 on average, with a range of 4 to 3 depending on location. Comparatively better condition than Douglas Ave. likely due to lower speed (traffic signals near both sides of bridge) and less volume of traffic, with fewer trucks. Despite significant chlorides present, lower overall time of wetness likely.
- Webs are uniform dark brown; tops of interior horizontal elements have chalking, but poultice shows only minor flaking. Bottoms of bottom flanges show discoloration and moderate staining, with some flaking. No delamination observed. Patina condition similar over traffic and near abutment.

TESTING PERFORMED:

- Color testing, chloride testing, tape testing performed at multiple locations.
- Core sample and chloride tests taken from hand brushed WT cross frame member (Index = 4) and compared to as-is poultice (63 ppm as-is, 35 ppm chalk brushed off by hand). Chalking appears to be mostly loose salt and dirt buildup, not entrapped/bonded with the rust.
- Chloride test profile on interior web showed variation in chloride concentration with test duration.
- Washing of interior girder over right lane with 40° nozzle, both with water alone and with CHLOR*RID.
  - CHLOR*RID had no apparent benefit, but washing proved effective at reducing surface chlorides (e.g. from 97 ppm to 30 ppm on top of the chalky bottom flange).

Figure 1. Typical interior girder conditions; good patina performance on web and flange, despite flange poultice.

Figure 2. Some discoloration on bottoms of flanges, but only minor flaking. Conditions near abutment similar to those over traffic.

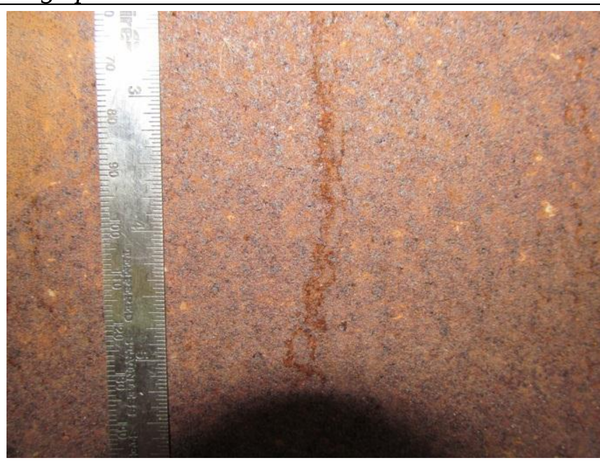

Figure 3. Web patina performing well (Index = 3.5).

Figure 4. Heavy flange chalking with only minor flaking (Index = 3).

Figure 5. Chloride test time vs. extraction efficiency profile taken on bottom of interior web (Index = 3).

Figure 6. Chloride tests adjacent to core location on both undisturbed and hand brushed poultice.

Douglas Avenue over I-35 and I-80 — 7726.1O080

NBI Structure No. 41331

MAP ID:	6
FACILITY CARRIED:	Douglas Avenue
FEATURES CROSSED:	I-35 and I-80
COUNTY:	077- Polk
LOCATION:	1.0 Mile North of US #6
LATITUDE:	41.62946286
LONGITUDE:	-93.77686594
YEAR BUILT:	2002
VERTICAL UNDER CLEARANCE:	17'-2"
AADT UNDER (ESTIMATED):	97,600
% TRUCKS UNDER (ESTIMATED):	15%

STRUCTURE DESCRIPTION:

Twelve continuous girders and two spans. Built in two stages; south stage 1 has five girders; north stage 2 has seven girders. Integral abutments, steeply sloped abutment walls. Cross frames between girders are single angle diagonals with WT bottom members.

SUMMARY OF CONDITION:

- Worst overall patina condition (especially given its age) of any bridge we inspected in Iowa.
- Patina index generally 2 (or locally 1) on interior surfaces, except over ramp, median, and close to abutments where all surfaces (except the tops of the bottom flanges) rise to index rating 3. Improved condition likely due to less direct traffic spray than fast, heavy main lane traffic. Interior coloration blotchy. Exterior fascia surfaces may rate as high as 3.5, probably due to natural washing, uniform dark brown.
- Interior bottom flanges severely chalked and delaminating on top, and flaking heavily on the bottom. Delamination spreads considerably up many girder webs directly over main traffic lanes.
- Bridge is very wide, and steep abutment slopes combine to create tunnel-like conditions. This, combined with fast, heavy traffic (with high truck percentage) may cause excessive salty spray to reach high on the girders. Also, south stage delamination appears substantially worse, possibly due to season of erection.

TESTING PERFORMED:

- Detailed visual inspection from ground and aerial lift.
- Color tests, and tape tests taken at over 8 exterior and interior locations. Chlorides tested at 6 locations. Representative scraping samples taken. Wire wheel grinding performed on a flaky interior girder web (with chloride tests reading 14 ppm before and after).
- Chlorides ranged from 1 ppm on a fascia web to 48 ppm on a chalky bottom flange.

Figure 1. Heavy poultice on interior flange with multiple thin layers of delamination forming.

Figure 2. Typical widespread delamination on web above traffic. Lower delaminations appear older, beginning to deteriorate again.

Figure 3. Close-up of web delamination progressing with scale inserted behind loose flake

Figure 4. Heavy deterioration typical of cross-frame members over traffic lanes.

Figure 5. Flaking and small delaminations on bottom of flanges over traffic.

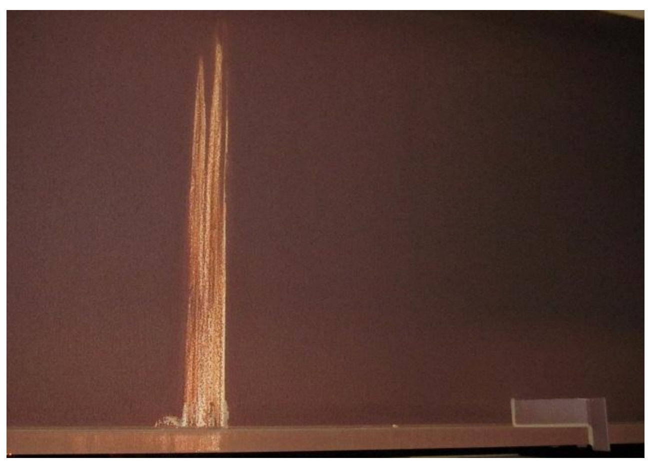

Figure 6. Example of staining on fascia girder. Patina locally under-developed underneath.

E. 14th Street (US-69) over I-235 — 7785.5S069

NBI Structure No. 40521

MAP ID:	7
FACILITY CARRIED:	E. 14th Street - US-69
FEATURES CROSSED:	I-235
COUNTY:	077- Polk
LOCATION:	At Junction I-235
LATITUDE:	41.59595419
LONGITUDE:	-93.59889547
YEAR BUILT:	2003
VERTICAL UNDER CLEARANCE:	17'-1"
AADT UNDER (ESTIMATED):	65,400
% TRUCKS UNDER (ESTIMATED):	4%

STRUCTURE DESCRIPTION:

Seven continuous girders, two spans. Integral abutments, vertical abutment slopewalls. Cross frames between girders are single angle diagonals with WT bottom members.

SUMMARY OF CONDITION:

- No delaminated areas of patina visible from below. Bottoms of bottom flanges show minor color variation and local staining. The west face of girder webs show staining above the ramp lane; the west fascia bottom flange has salty staining. Otherwise, color is uniform dark brown. Index of these surfaces is 3.5 to 4.
- Top faces of interior horizontal elements have significant poultice corrosion and flaking with Index 2 to 3.
- Current NBI Superstructure Rating = 7. This rating is representative of conditions viewed from the ground, but consideration should be given to downgrading the rating based on observations from the aerial lift.

TESTING PERFORMED:

- Visual inspection from ground and aerial lift.
- Tape and chloride testing on east fascia girder over westbound I-235 left lane.
  - Exterior web and top of bottom flange had respective index ratings of 3.5 to 3, with no measured chlorides.
  - Bottom of bottom flange rated at index = 2 and a 2 ppm chloride concentration measured.
- Tape comparison of interior girder webs facing toward and away from traffic over westbound left lane.
  - Tapes away from traffic pulled away larger, denser flakes (Index = 3) than those facing traffic (Index 3.5 to 3). However, tapes facing traffic showed more salt and dirt deposits. Difference is likely insignificant; it highlights the sensitivity and limitations of the patina index and tape test.

Figure 1. Bottom flanges exhibiting some mild reddish discoloration and possible flaking near pier over eastbound left shoulder.

Figure 2. More distinct spots of local discoloration visible near middle of south span.

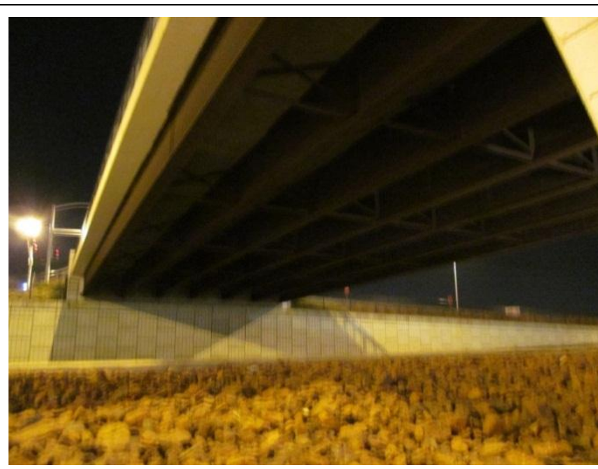

Figure 3. Overall photo of span over westbound I-235.

E. 12th Street over I-235 7709.1O235

NBI Structure No. 42871

MAP ID:	7
FACILITY CARRIED:	SE 12th Street
FEATURES CROSSED:	I-235
COUNTY:	077- Polk
LOCATION:	5.2 miles East of Junction IA #28
LATITUDE:	41.595265
LONGITUDE:	-93.60295557
YEAR BUILT:	2002
VERTICAL UNDER CLEARANCE:	18’-0”
AADT UNDER (ESTIMATED):	65,100
% TRUCKS UNDER (ESTIMATED):	4%

STRUCTURE DESCRIPTION:

Six continuous girders, two spans. Integral abutments, vertical abutment slopewalls. Cross frames between girders are single angle diagonals with WT bottom members. A large utility pipe runs longitudinally along the bridge. The bridge appears to have had instrumentation installed at some locations at some point based on wiring and other remnants left in place.

SUMMARY OF CONDITION:

- No delaminated areas of patina visible from below. Bottoms of bottom flanges show minor color variation and local staining. Also, there is white staining on the west fascia girder bottom flange bottom; otherwise, color is uniform dark brown. Index of these surfaces is generally 3.5 to 4.
- Top faces of interior horizontal elements likely have significant poultice corrosion and flaking with Index 2 to 3, based on consistent results for other similar nearby bridges in Field Selection 7 inspected with an aerial lift.
- Current NBI Superstructure Rating = 8. This rating is representative of conditions viewed from the ground, but consideration should be given to downgrading the rating based on condition of patina on top of horizontal elements.

TESTING PERFORMED:

- Visual inspection from ground.
    - Some of discolored areas and stains appear consistent with presence of objects (e.g. instrumentation, construction period) that were subsequently removed.

Figure 1. White, salty staining on west fascia girder (toward oncoming traffic) bottom flange south of pier.

Figure 2. Rectangular, reddish stains on bottom flanges. Also note grayish staining on interior web of fascia girder beyond. Such stains occasionally noticed throughout Field Selection 7.

Figure 3. Overall photo of the span over eastbound I-235.

E. 9th Street over I-235 — 7709.0O235

NBI Structure No. 4111

MAP ID:	7
FACILITY CARRIED:	East 9th Street
FEATURES CROSSED:	I-235
COUNTY:	077- Polk
LOCATION:	5.1 miles East of Junction IA #28
LATITUDE:	41.59483797
LONGITUDE:	-93.60645962
YEAR BUILT:	2001
VERTICAL UNDER CLEARANCE:	18'-2"
AADT UNDER (ESTIMATED):	65,100
% TRUCKS UNDER (ESTIMATED):	4%

STRUCTURE DESCRIPTION:

Six continuous girders, four spans. Integral abutments. Cross frames between girders are single angle diagonals with WT bottom members.

SUMMARY OF CONDITION:

- No delaminated areas of patina visible from below. Light colored localized stains on west face of webs over exit median. Minor color variation and flaking on bottoms of bottom flanges. White staining on west fascia bottom flange over I-235 EB; otherwise, uniform dark brown. Index of these surfaces is 3.5 to 4.
- Top faces of interior horizontal elements have significant poultice corrosion and flaking with Index 2 to 3.
- Current NBI Superstructure Rating = 8. This rating is representative of conditions viewed from the ground, but consideration should be given to downgrading the rating based on condition of patina on top of horizontal elements.

TESTING PERFORMED:

- Visual inspection from ground and aerial lift.
- Washing over westbound left lane and shoulder of 2nd interior girder (west face) from west fascia girder. 40° nozzle used on web and tops of bottom flange. It was ineffective at removing the poorly adhered portions of the patina. Surface chlorides were reduced by washing (where tests did not leak), but trapped chlorides likely not affected by washing. Decision to evaluate 0° nozzle arose from washing this bridge.
- Supplemental tape test and chloride tests performed at this location before and after washing. Hand brushing and wire wheel grinding also performed for comparison.
    - Before washing: Web index = 3, top of bottom flange index = 2. Top of flange chlorides = 45 ppm on poultice, 30 ppm after hand brushing, 23 ppm after wire wheel grinding.
    - After washing, wire wheel area chlorides down to 8 ppm.

Figure 1. Overall condition of girders and bracing viewed from below, here near pier.

Figure 2. Chloride tests with some leaking on chalky poultice of bottom flange before washing.

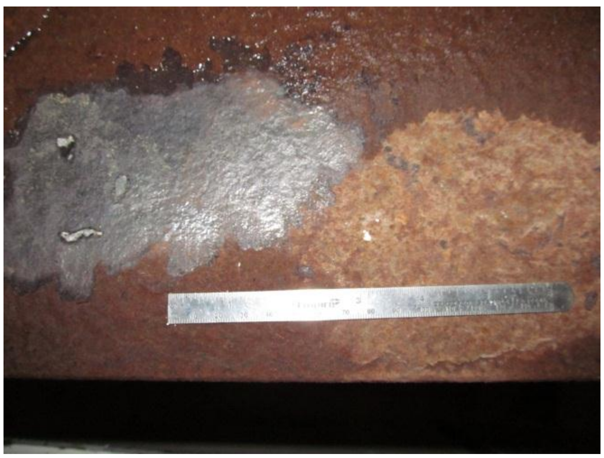

Figure 3. Close-up of wire wheel ground area and adjacent as-is poultice after washing and drying.

Figure 4. Test area after washing and partial drying: wire wheel area on left, wire brush area on far right.

Figure 5. Washing as-is: poultice reduced, but delamination remains.

Figure 6. Washing after hand brushing of poultice: Cleaner, but delaminated patina remains.

Pennsylvania Avenue over I-235 — 7708.9O235

NBI Structure No. 42841

MAP ID:	7
FACILITY CARRIED:	Pennsylvania Avenue
FEATURES CROSSED:	I-235
COUNTY:	077- Polk
LOCATION:	5.0 miles East of Junction IA #28
LATITUDE:	41.59493133
LONGITUDE:	-93.60829526
YEAR BUILT:	2002
VERTICAL UNDER CLEARANCE:	18'-3"
AADT UNDER (ESTIMATED):	65,100
% TRUCKS UNDER (ESTIMATED):	4%

STRUCTURE DESCRIPTION:

Seven continuous girders, two spans. Integral abutments, moderately skewed. Cross frames between girders are single angle diagonals with WT bottom members.

SUMMARY OF CONDITION:

- No delaminated areas of patina visible from below. Light colored localized stains on west face of webs over exit median. Minor color variation and flaking on bottoms of bottom flanges; otherwise, uniform dark brown. Index of these surfaces is generally 3.5 to 4.
- Top faces of interior horizontal elements likely have significant poultice corrosion and flaking with Index 2 to 3, based on consistent results for other similar bridges in Field Selection 7 inspected with an aerial lift.
- Current NBI Superstructure Rating = 9. This rating is representative of conditions viewed from the ground, but consideration should be given to downgrading the rating based on condition of patina on top of horizontal elements.

TESTING PERFORMED:

- Visual inspection from the ground.

Figure 1. Patina in good condition on all surfaces visible from ground; here near pier.

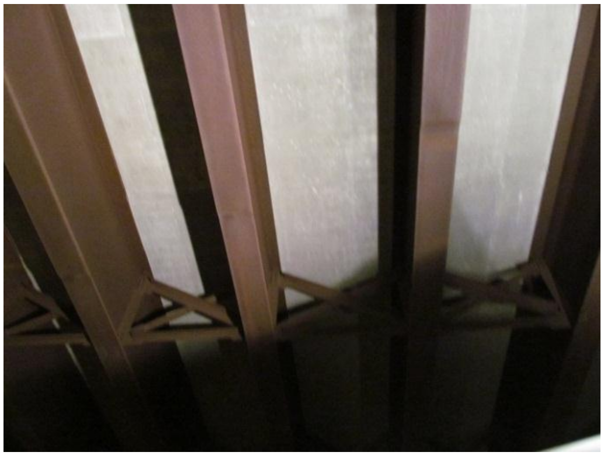

Figure 2. Uniform, dark patina performing well near mid-span.

Figure 3. Some localized blotchy stains and flaking; otherwise patina is uniform when viewed from the ground.

East 6th Street over I-235 — 7708.8O235

NBI Structure No. 608680

MAP ID:	7
FACILITY CARRIED:	East 6th Street
FEATURES CROSSED:	I-235
COUNTY:	077- Polk
LOCATION:	4.9 miles East of Junction IA #28
LATITUDE:	41.59514993
LONGITUDE:	-93.61034285
YEAR BUILT:	2002
VERTICAL UNDER CLEARANCE:	17’-3”
AADT UNDER (ESTIMATED):	77,600
% TRUCKS UNDER (ESTIMATED):	4%

STRUCTURE DESCRIPTION:

Six continuous girders, two spans. Integral abutments. Cross frames between girders are single angle diagonals with WT bottom members.

SUMMARY OF CONDITION:

- No delaminated areas of patina visible from below. Some white staining and flakiness noted on bottom of bottom flange of west fascia girder. Also a stain on the east fascia web near the north abutment; otherwise, uniform dark brown. Index of these surfaces is generally 3.5 to 4.
- Top faces of interior horizontal elements have significant poultice corrosion and flaking with Index 2 to 3.
- Current NBI Superstructure Rating = 7. This rating is representative of conditions viewed from the ground, but consideration should be given to downgrading the rating based on condition of patina on top of horizontal elements.

TESTING PERFORMED:

- Visual inspection from ground and aerial lift.
- Tape test profiles of west fascia girder and first interior girder from west; also on cross-frame diagonal between them. Results show index ratings of 3.5 on exterior faces down to 2 on interior surfaces.
- Scrapings taken adjacent to some tape test locations.

Figure 1. Index = 3.5 to 3 patina on exterior fascia surfaces.

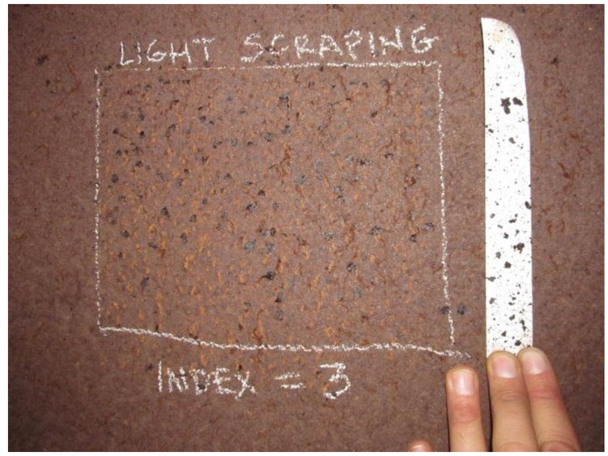

Figure 2. Interior middle of web tape test and hand scraping of loose flake (dark spots). Index later determined to be 2 based on tape flake size.

Figure 3. Index = 2 patina on vertical face of cross-brace where tape test conducted.

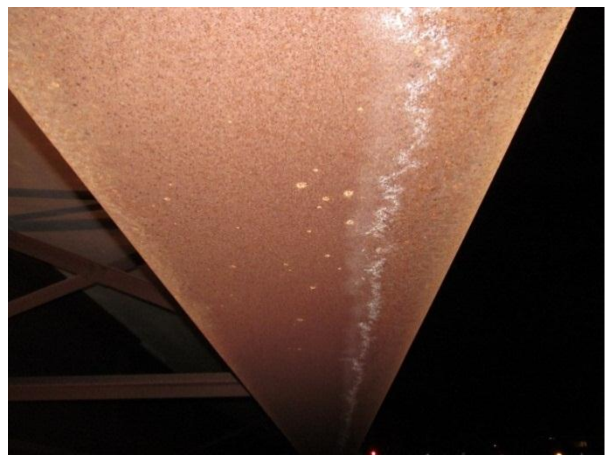

Figure 4. White staining on bottom flange of west fascia on eastbound lanes (side toward traffic).

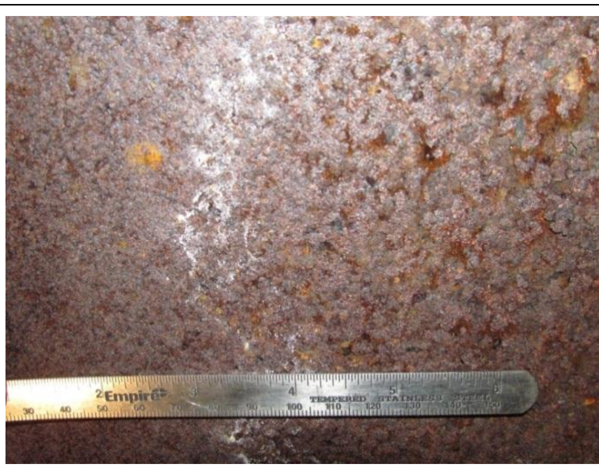

Figure 5. Close-up of discoloration and flaking on bottom flange adjacent to staining, Index = 2.

Figure 6. Delaminated, heavy poultice corrosion on interior bottom flange.

I-235 over the Des Moines River and I-235 E.B Entrance Ramp at 2nd Avenue — 7708.5S235 and 7708.5A235

NBI Structure No. 42740 and 42761

MAP ID:	7
FACILITY CARRIED:	I-235 and I-235 E.B. Entrance Ramp
FEATURES CROSSED:	Des Moines River and W. River Dr.
COUNTY:	077- Polk
LOCATION:	4.6 miles East of Junction IA #28
LATITUDE:	41.5955709
LONGITUDE:	-93.61701132
YEAR BUILT:	Ramp 2003, Mainline Rebuilt in 2007
VERTICAL UNDER CLEARANCE:	13'-6"
AADT UNDER (ESTIMATED):	N/A
% TRUCKS UNDER (ESTIMATED):	N/A

STRUCTURE DESCRIPTION:

Twelve continuous girders support the mainline and four continuous girders support the ramp. Structure as a whole is approximately 10 spans, with ramps tying into the structures on the north and south sides at the west end of the bridge. Shared substructure at some locations. Conventional abutments. Channel diaphragms between girders.

SUMMARY OF CONDITION:

- Overall, patina in excellent condition on all surfaces, both interior and exterior, due to low moisture and salt exposure (Index = 3.5 to 4). Uniform dark brown coloration, except for a few spots of under-developed patina.
- Entrance ramp north fascia girder showing signs of distress where it is likely receiving direct snow/salt spray from adjacent I-235 eastbound. Full range from Index 1.5 to 4 present, but in this case typical trends reversed, as exterior fascia surfaces seeing direct spray rapidly deteriorating, while interior surfaces performing well.

TESTING PERFORMED:

- Core sample taken from diaphragm web on I-235 westbound bridge, over southbound lane of access road west of the river.
    - Chloride test at this location: 1 ppm
    - Tape test at this location: Index = 4, very small rust flakes.
- Tape tests at underdeveloped patina on diaphragm web over access road on I-235 eastbound (Index = 5).
- Tape test profile and scrapings taken on north fascia girder of south ramp.
- Visual inspection from ground and aerial lift.

Figure 1. Delamination of top of exterior bottom flange and web of north fascia girder on I-235 eastbound entrance ramp.

Figure 2. Bottom of bottom flange delaminations, north fascia girder of entrance ramp.

Figure 3. Interior side of entrance ramp north fascia girder demonstrating good patina performance.

Figure 4. Interior girders of westbound mainline bridge showing good patina performance.

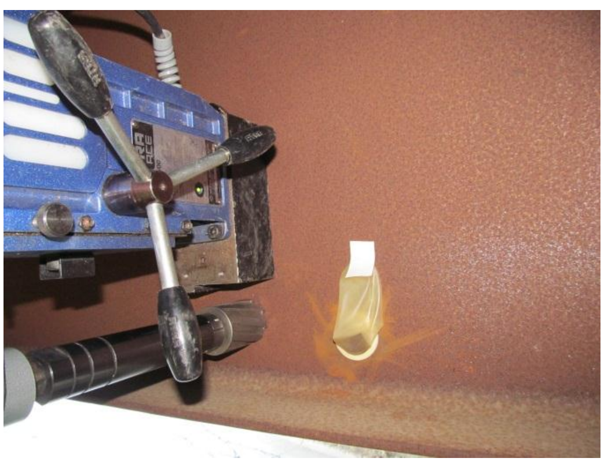

Figure 5. Magnetic drill coring a channel diaphragm web on westbound I-235 bridge.

Figure 6. Areas of underdeveloped patina due to spill during construction or mill scale (Index=5).

2nd Avenue over I-235 — 7708.3O235

NBI Structure No. 42731

MAP ID:	7
FACILITY CARRIED:	2nd Avenue
FEATURES CROSSED:	I-235
COUNTY:	077- Polk
LOCATION:	4.4 miles East of Junction IA #28
LATITUDE:	41.59627968
LONGITUDE:	-93.61968568
YEAR BUILT:	2003
VERTICAL UNDER CLEARANCE:	19'-9"
AADT UNDER (ESTIMATED):	82,300
% TRUCKS UNDER (ESTIMATED):	4%

STRUCTURE DESCRIPTION:

Six continuous girders, three spans with ramp structure (7708.3A235) tying into north span girders from the west side. Conventional abutments. Cross frames between girders are WT K-braces. Stiffened wide flange diaphragms over piers.

SUMMARY OF CONDITION:

- No delaminated areas of patina visible from below. Some localized color variation and flakiness noted on bottom of bottom flanges, webs and top flanges; otherwise uniform dark brown. Index of these surfaces is 3.5 to 4.
- Top faces of interior horizontal elements have significant poultice corrosion and flaking with Index 2 to 3.
- Current NBI Superstructure Rating = 8. This rating is representative of conditions viewed from the ground, but consideration should be given to downgrading the rating based on condition of patina on top of horizontal elements.

TESTING PERFORMED:

- Visual inspection only, including use of aerial lift.

Figure 1. East half of bridge girders near pier; generally good patina condition viewed from below.

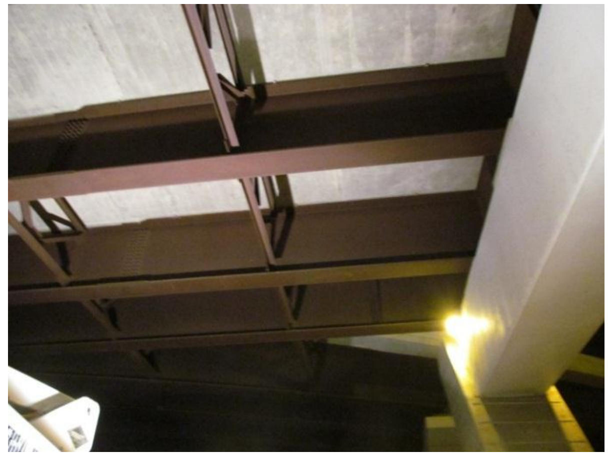

Figure 2. West half of girders near pier, where ramp comes in (background).

Figure 3. Stiffened I-beam diaphragm at pier.

Figure 4. Typical K-brace cross-frame with bird droppings on girder bottom flanges.

Figure 5. Delaminating patina with heavy poultice corrosion on interior girder bottom flange.

Figure 6. Interior girder bottom flange with heavy poultice corrosion viewed from arm's length.

2nd Avenue Ramp over I-235 — 7708.3A235

NBI Structure No. 42721

MAP ID:	7
FACILITY CARRIED:	Ramp
FEATURES CROSSED:	S-W Connection over WB I-235
COUNTY:	077- Polk
LOCATION:	4.4 miles East of Junction IA #28
LATITUDE:	41.59595208
LONGITUDE:	-93.62022787
YEAR BUILT:	2002
VERTICAL UNDER CLEARANCE:	17’-9”
AADT UNDER (ESTIMATED):	82,300
% TRUCKS UNDER (ESTIMATED):	4%

STRUCTURE DESCRIPTION:

Four curved continuous girders, two spans of varying length terminating at 2nd Avenue bridge girders. Conventional abutments. Cross frames between girders are WT K-braces.

SUMMARY OF CONDITION:

- No delaminated areas of patina visible from below. Some localized color variation and flakiness noted on bottom of bottom flanges, webs and top flanges; otherwise uniform dark brown. Index of these surfaces is 3.5 to 4.
- Top faces of interior horizontal elements have significant poultice corrosion and flaking with Index 2 to 3.
- Current NBI Superstructure Rating = 8. This rating is representative of conditions viewed from the ground, but consideration should be given to downgrading the rating based on condition of patina on top of horizontal elements.

TESTING PERFORMED:

- Visual inspection only, including use of aerial lift.

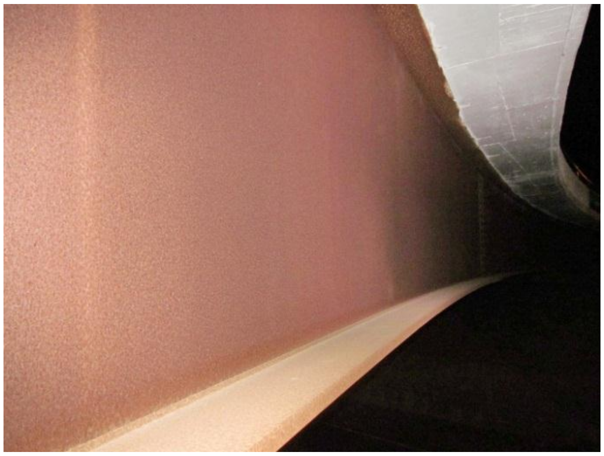

Figure 1. Excellent patina performance (Index=4) on exterior fascia surfaces.

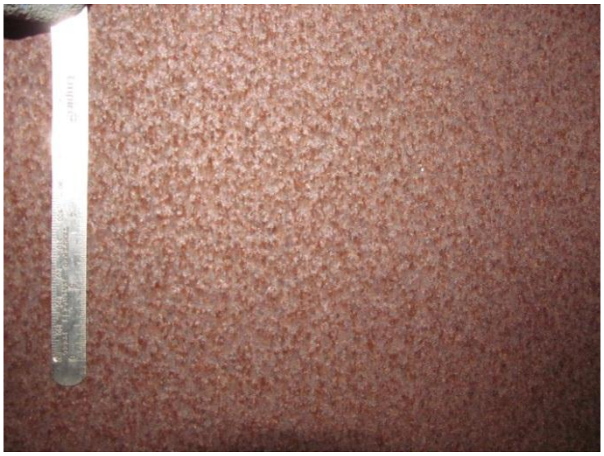

Figure 2. Close-up of exterior fascia web patina.

Figure 3. Light poultice corrosion without flaking or deterioration on fascia girder flange.

Figure 4. Heavy poultice corrosion with delaminated flaking on interior bottom flange.

Figure 5. Bird droppings contributing to poultice on interior bottom flange.

Figure 6. Some localized discoloration and flaky areas on otherwise good patinas near pier.

3rd Street over I-235 — 7708.2O235

NBI Structure No. 42711

MAP ID: 7

FACILITY CARRIED: 3rd Street

FEATURES CROSSED: I-235

COUNTY: 077- Polk

LOCATION: 4.3 miles East of Junction IA #28

LATITUDE: 41.59580845

LONGITUDE: -93.6215435

YEAR BUILT: 2003

VERTICAL UNDER CLEARANCE: 24'-0"

AADT UNDER (ESTIMATED): 74,500

% TRUCKS UNDER (ESTIMATED): 4%

STRUCTURE DESCRIPTION:

Seven continuous girders, three spans. Conventional abutments. Channel diaphragms between girders. Ramp enters north span on east side.

SUMMARY OF CONDITION:

- No delaminated areas of patina visible from below; some color variation and flakiness noted on bottom of bottom flanges and on webs near south abutment; otherwise uniform dark brown. Index of these surfaces is 3.5 to 4.
- Top face of horizontal elements has significant poultice corrosion and flaking with Index 2 to 3.
- Current NBI Superstructure Rating = 8. This rating is representative of conditions viewed from the ground, but consideration should be given to downgrading the rating based on condition of patina on top of horizontal elements.

TESTING PERFORMED:

- Visual inspection, including use of aerial lift.
- Core sample taken from bottom of web of interior diaphragm in south span. Other tests conducted here include:
    - Tape test: Index = 3.5, flake size = 0.5 mm to 2 mm, medium density.
    - Chloride test: 6 ppm

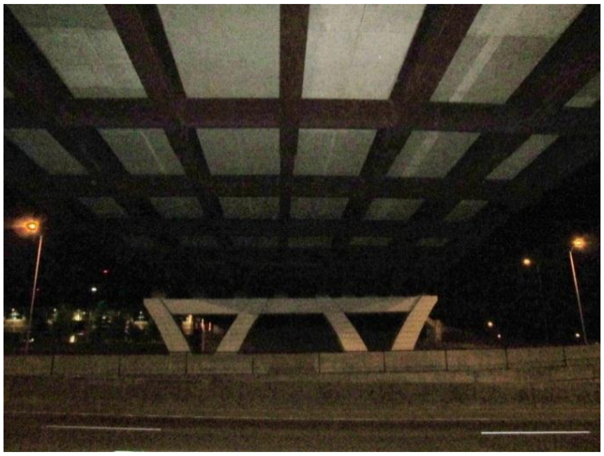

Figure 1. Overall view toward north two spans and north pier.

Figure 2. Girders and diaphragms near south pier; appear in good condition from below.

Figure 3. Middle of south span.

Figure 4. Heavy poultice corrosion on diaphragm and girder flange at core location.

Figure 5. Tape and chloride tests also taken adjacent to core.

Figure 6. Detail of patina condition on diaphragm web adjacent to core. Index=3.5.

5th Avenue over I-235 — 7708.1O235

NBI Structure No. 608950

MAP ID:	7
FACILITY CARRIED:	5th Avenue
FEATURES CROSSED:	I-235
COUNTY:	077- Polk
LOCATION:	4.2 miles East of Junction IA #28
LATITUDE:	41.59570843
LONGITUDE:	-93.62464277
YEAR BUILT:	2003
VERTICAL UNDER CLEARANCE:	17’-8”
AADT UNDER (ESTIMATED):	74,500
% TRUCKS UNDER (ESTIMATED):	4%

STRUCTURE DESCRIPTION:

Five continuous girders, two spans. Integral abutments. Cross frames between girders are single angle diagonals with WT bottom members.

SUMMARY OF CONDITION:

- No delaminated areas of patina visible or color variation noted on surfaces visible from below; uniform dark brown. Index of these surfaces is 3.5 to 4.
- However, top face of horizontal elements chalky and flaky with Index 2 to 3, based on limited inspection from the aerial lift and uniformity of conditions observed in detail on other bridges in this field selection.
- Current NBI Superstructure Rating = 9. This rating is representative of conditions viewed from the ground, but consideration should be given to downgrading the rating based on condition of patina on top of horizontal elements.
- Stains or spill on south fascia and 1st interior girders over center lane.

TESTING PERFORMED:

Visual inspection only.

Figure 1.South span over eastbound I-235. Some staining noted on fascia girder and 1st interior girder over the center lane, but not readily visible in this photo.

Figure 2. Girders and cross-frames near center pier; no significant deterioration visible from below.

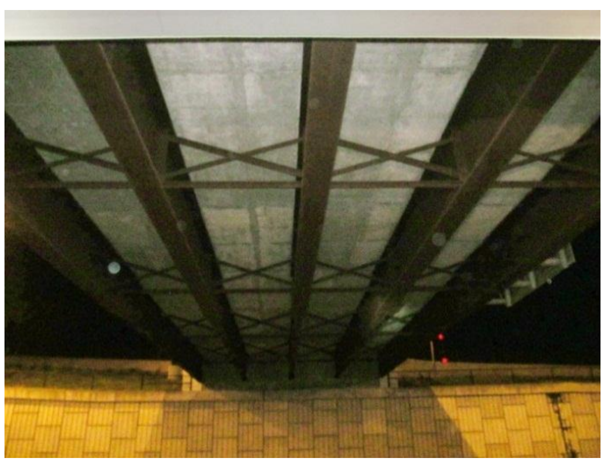

Figure 3. North span over westbound I-235.

6th Avenue over I-235 — 7708.0O235

NBI Structure No. 42621

MAP ID:	7
FACILITY CARRIED:	6th Avenue
FEATURES CROSSED:	I-235
COUNTY:	077- Polk
LOCATION:	4.1 miles East of Junction IA #28
LATITUDE:	41.59568253
LONGITUDE:	-93.62567366
YEAR BUILT:	2004
VERTICAL UNDER CLEARANCE:	16’-10”
AADT UNDER (ESTIMATED):	74,500
% TRUCKS UNDER (ESTIMATED):	4%

STRUCTURE DESCRIPTION:

Eight continuous girders, two spans. Integral abutments. Cross frames between girders are single angle diagonals with WT bottom members.

SUMMARY OF CONDITION:

- No delaminated areas of patina visible or color variation noted on surfaces visible from below; uniform dark brown. Index of these surfaces is 3.5 to 4.
- However, top face of horizontal elements chalky and flaky with Index 2 to 3, based on limited inspection from the aerial lift and uniformity of conditions observed in detail on other bridges in this field selection.
- Current NBI Superstructure Rating = 9. This rating is representative of conditions viewed from the ground, but consideration should be given to downgrading the rating based on condition of patina on top of horizontal elements.

TESTING PERFORMED:

Visual inspection only.

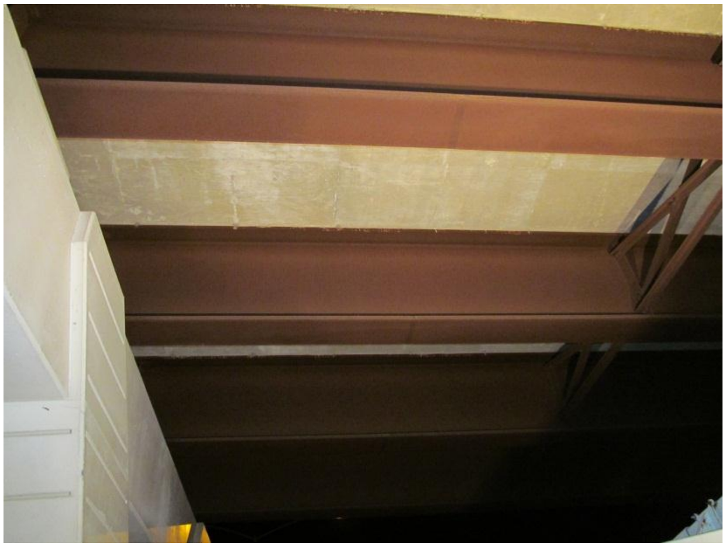

Figure 1. Girders near the intermediate pier; no signs of significant deterioration visible.

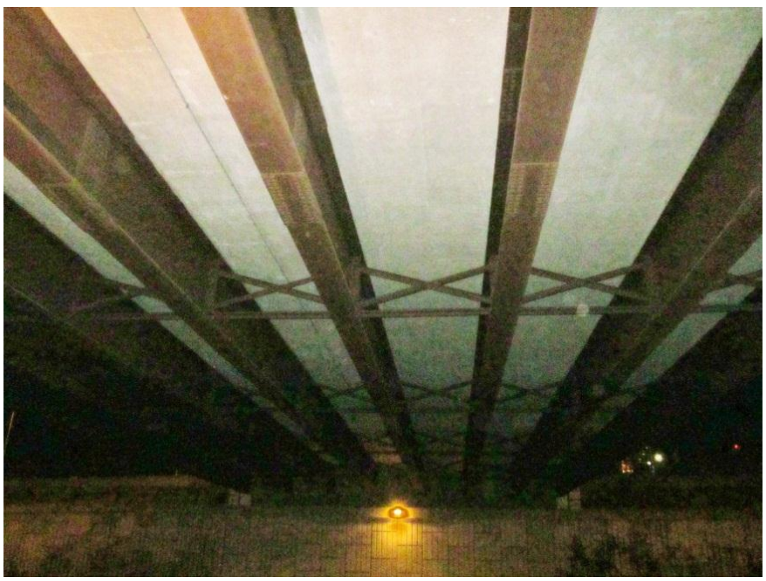

Figure 2. Overall photo of the second span.

7th Street over I-235 — 7707.9O235

NBI Structure No. 42611

MAP ID: 7

FACILITY CARRIED: 7th Street

FEATURES CROSSED: I-235/3rd Street Ramp B

COUNTY: 077- Polk

LOCATION: 4.0 miles East of Junction IA #28

LATITUDE: 41.59568757

LONGITUDE: -93.62686601

YEAR BUILT: 2003

VERTICAL UNDER CLEARANCE: 16’-10”

AADT UNDER (ESTIMATED): 74,500

% TRUCKS UNDER (ESTIMATED): 4%

STRUCTURE DESCRIPTION:
Six continuous girders, two spans. Integral abutments. Cross frames between girders are single angle diagonals with WT bottom members.

SUMMARY OF CONDITION:

- No delaminated areas of patina visible or color variation noted on surfaces visible from below; uniform dark brown. Index of these surfaces is 3.5 to 4.
- However, top face of horizontal elements chalky and flaky with Index 2 to 3, based on limited inspection from the aerial lift and uniformity of conditions observed in detail on other bridges in this field selection.
- Current NBI Superstructure Rating = 9. This rating is representative of conditions viewed from the ground, but consideration should be given to downgrading the rating based on condition of patina on top of horizontal elements.

TESTING PERFORMED:
Visual inspection only.

Figure 1. Girder and cross-frames near mid-span; representative of conditions throughout the structure.

Figure 2. Girders and cross-frames near the intermediate pier.

I-80 EB and I-29 SB over Indian Creek 7802.4R080

NBI Structure No. 44680

MAP ID: 8

FACILITY CARRIED: SB I-29, EB I-80

FEATURES CROSSED: Indian Creek

COUNTY: 078- Pottawattamie

LOCATION: 2.4 Miles East of Nebraska State Line

LATITUDE: 41.23217882

LONGITUDE: -95.86501931

YEAR BUILT: 1968 original, possibly widened in 1990's

VERTICAL UNDER CLEARANCE: N/A

AADT UNDER (ESTIMATED): N/A

% TRUCKS UNDER (ESTIMATED): N/A

STRUCTURE DESCRIPTION:

Two continuous three-span weathering steel girders (rolled wide flange sections in lieu of plate girders) used for widening adjacent to the original painted steel construction. The original 1968 bridge was widened with the weathering steel girders on the north side at an unknown date, possibly the 1990's based on steel appearance. Clear distance between eastbound and westbound bridges is only 19 feet. Channel diaphragms. Conventional abutments.

SUMMARY OF CONDITION:

- Interior patina surfaces are in excellent condition with Index = 3.5 to 4. Little to no salt exposure and low moisture; Indian Creek is small and though the bridge is low, does not likely contribute much moisture.
- North fascia exposed surfaces likely see extensive direct snow/salt spray from westbound I-80 bridge given proximity. Lots of delamination and flaking on exposed web and top and bottom of fascia bottom flange. Average Index = 2 on these surfaces. Similar to conditions on I-235 entrance ramp structure at 2nd Avenue (7708.5A235).

TESTING PERFORMED:

- Visual inspection on foot only.
- Chloride and tape tests on north fascia girder near west abutment.
  - Chlorides ranged from 1 ppm on interior web to 17 ppm on bottom of flange, with range between. Tests indicate that despite natural washing, chlorides retained beneath flaking and in pits. Winter damage may progress too rapidly for natural washing to remove salts, and so they penetrate and cause significant deterioration, unlike fascia girders without direct spray from adjacent roads.
  - Index on exposed surfaces was 1 on bottom of flange, 1.5 on top of flange, 2 at bottom of exterior web, and 2.5 on middle of exterior web face.

Figure 1. West pier showing framing arrangement and tie-in to original structure.

Figure 2. Heavy delamination of fascia bottom flange top (without poultice); also flaky on web.

Figure 3. Close up of delaminations and discoloration of bottom of fascia girder bottom flange.

Figure 4, Interior top of bottom fascia flange with light poultice corrosion, but minimal flakiness.

Figure 5. Interior web performing well.

Figure 6. Fascia problems continue over main span.

US-218 over IA-22 — 9280.9R218

NBI Structure No. 605593

MAP ID: 9

FACILITY CARRIED: NB US-218

FEATURES CROSSED: IA-22

COUNTY: 092 - Washington

LOCATION: At Junction IA #22 and US #218

LATITUDE: 41.48677802

LONGITUDE: -91.55138851

YEAR BUILT: 1995

VERTICAL UNDER CLEARANCE: 17’-1”

AADT UNDER (ESTIMATED): 4,600

% TRUCKS UNDER (ESTIMATED): 10%

STRUCTURE DESCRIPTION:

Five continuous plate girders, three spans. Width approximately 45 feet, with 9’-3” approximate girder spacing. Integral abutments, mild skew, concrete-lined embankments. Cross-frames between girders are single angle diagonals with a WT bottom member. Adjacent bridge carrying southbound US-218 is roughly 53 feet away (clear distance). Drainage deflector plates only installed on exterior fascia flanges; water can migrate on interior from span to span.

SUMMARY OF CONDITION:

- Patina condition rates at Index = 3 on average; interior vertical surfaces are Index = 3 to 3.5, with problem zones reaching Index = 2 to 2.5, especially at bottoms of interior girder webs and interior bottom flanges. Exterior fascia surfaces rate Index = 4. Current NBI superstructure rating is 8, consider lowering based on patina conditions.
- Uniform dark brown coloration, except for light colored poultice noted on top of horizontal elements.
- Bottom of bottom flanges worse over traffic (direct spray); poultice and deterioration of tops of bottom flanges worse near south abutment, possibly due to drainage of contaminants along bridge slope to south.

TESTING PERFORMED:

- Detailed testing performed on interior and fascia girders near south abutment, as well as west fascia girder over IA-22 eastbound right shoulder, including tape, chloride, and color tests, with scrapings also taken.
  - Poultice flakier on interior girders than exterior girders at south abutment, with scraped delaminations larger than 1 inch. Interior top of fascia bottom flange showed poultice without delamination. Wetted with water and blotted dry to explore solubility of chalky layer, i.e. saltiness.
  - Chlorides measured were as low as 0 ppm on exterior vertical surfaces; on interior bottoms of flanges reached 8 ppm over traffic and over 27 ppm on top of interior bottom flange poultice.

Figure 1. View of south pier looking north; note lack of drainage deflector plates on bottom flanges, typ.

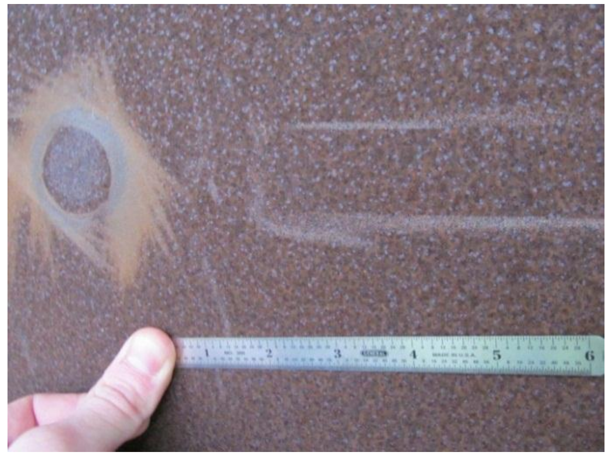

Figure 2. Exterior of east fascia web near south abutment. Index = 4 by tape, chlorides = 0 ppm.

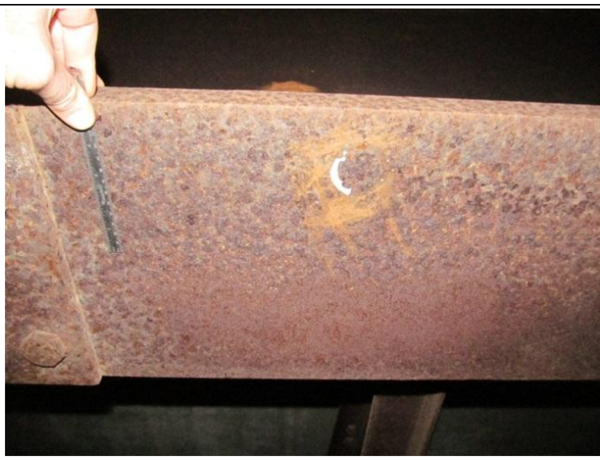

Figure 3. Heavy flaking (Index = 2) on bottom of west fascia bottom flange over shoulder.

Figure 4. Delamination of interior girder bottom flange with heavy poultice subjected to light scraping.

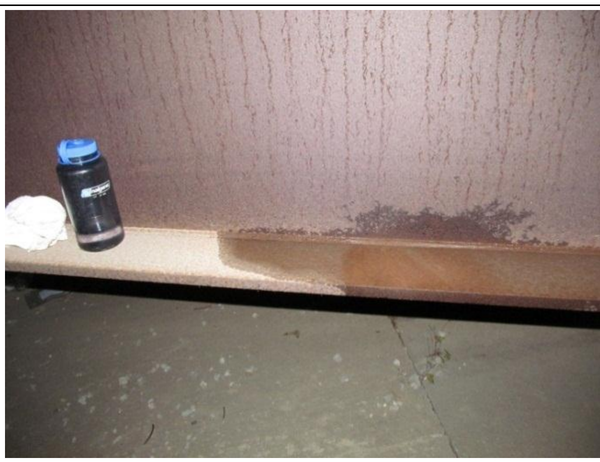

Figure 5. Poultice on east fascia interior side (not flaky). Washed with water and blotted dry.

Figure 6. Washed area of top of flange patina after fully dried; adherent, well-behaved beneath chalking.

US-75 over Business-75 and Railroad — 9799.5L075 and 9799.5R075

NBI Structure No. 607980 and 607985

MAP ID: 10

FACILITY CARRIED: US-75

FEATURES CROSSED: Business 75; railroad

COUNTY: 097 - Woodbury

LOCATION: 5.8 miles North of Junction Iowa #12

LATITUDE: 42.55265478

LONGITUDE: -96.34160283

YEAR BUILT: 1999

VERTICAL UNDER CLEARANCE: 17'-11"

AADT UNDER (ESTIMATED): 8,000

% TRUCKS UNDER (ESTIMATED):

STRUCTURE DESCRIPTION:

Both bridges have four curved plate girders continuous over five spans, with conventional abutments. Cross-frames between girders are WT k-braces, with wide flange diaphragms and k-bracing at the abutments. Steel is painted near abutments. Relatively high clearance over roadway, narrow decks, long spans, and deep girders. Clear distance between NB 607985 and SB 607980 is sufficient to prevent significant interaction on fascia girders due to snow/salt spray from adjacent bridge.

SUMMARY OF CONDITION:

- Typically, the patina condition index rating for these bridges ranges from 4 on the middle and upper portions of the girders and frames to 3 on the bottom flanges and bases of the webs.
- The west fascia girder of each bridge has heavy salt staining on the underside of the bottom flange and larger rust flakes (i.e. Index = 2). Chalking on tops of bottom flanges is slight to moderate.
- Bridge decks have numerous transverse cracks, particularly in the middle spans. Evidence of salt contaminated water leaking onto steel below cracks, with localized delamination/flaking of the top flange beneath the crack (possibly Index = 1 locally). The patina of the lower elements beneath each crack is typically reduced by at least 0.5 index points compared to adjacent surfaces away from the cracks. Sealing the deck cracks will address the root cause of the localized areas of poor patina performance.

TESTING PERFORMED:

- Chloride and tape testing on east fascia girder at north abutment of southbound bridge.
  - Bottom of bottom flange away from deck cracks showed light salt staining and flaking. (Index = 3, chlorides measured at 9 ppm). Other surfaces, Index = 4.
- Chloride and tape test profiles below deck cracks on west fascia girder of southbound bridge over BUS-75 left shoulder show that patina beneath cracks is in worse condition and has higher surface chlorides (up to 23 ppm and Index = 2 on bottom of bottom flange) than areas away from cracks. Worst deterioration on southbound bridge is on west fascia girder, likely because salty snow is plowed to this shoulder of bridge.

Figure 1. Typical middle bay of southbound bridge; note regular cracking with efflorescence and heavy salt staining on west fascia girder bottom flange.

Figure 2. Exterior of west fascia girder on southbound bridge showing localized patina deterioration on all surfaces beneath cracks.

Figure 3. Other girders of southbound bridge show little change in patina condition beneath cracks.

Figure 4. Heavy deterioration/delamination of west fascia girder top flange at crack, possibly Index = 1.

Figure 5. Condition of bottom of flange of east fascia near north abutment considerably better than west fascia (Index = 3).

Figure 6. Typical condition of other interior surfaces away from deck cracks typically Index = 3 to 4, with little to no surface chlorides measured.

FM RD A-34 over I-35 — 9811.3O035

NBI Structure No. 600200

MAP ID: 11

FACILITY CARRIED: FM RD A-34

FEATURES CROSSED: I-35

COUNTY: 098 - Worth

LOCATION: 7.3 Miles North of Iowa #9

LATITUDE: 43.3894913

LONGITUDE: -93.34941096

YEAR BUILT: 1970

VERTICAL UNDER CLEARANCE: 16’-7”

AADT UNDER (ESTIMATED): 17,800

% TRUCKS UNDER (ESTIMATED): 28%

STRUCTURE DESCRIPTION:

Four continuous plate girders over four spans. Conventional abutments without skew. Channel diaphragms between girders, with wide flange end diaphragms at abutments. Drainage deflector plates installed on all girder flanges, but do not appear original. Minor staining of substructure. Sloped embankments covered with concrete.

SUMMARY OF CONDITION:

- Patina in good condition considering over 40 years of service; however, interior horizontal surfaces (top and bottom) directly over traffic lanes showing signs of more substantial patina deterioration.
- Index typically = 3.5 on all fascia or other exposed surfaces, whether over traffic or near abutments. Index rating = 3 for interior surfaces near abutments (even bottom flanges, which show moderate poultice but minor flaking), Index = 2 or worse for all interior surfaces over traffic, especially on the bottom flanges and lower portions of the webs. Drainage deflectors may be reducing bottom flange damage in non-traffic bays.
- Concrete deck in good condition; light traffic above means virtually all salts and water come from below.
- Direct salty spray from high-speed truck traffic over time likely driving deterioration over traffic lanes.

TESTING PERFORMED:

- Tape test profiles of fascia and interior girders over northbound right shoulder and near east abutment.
    - Index ranged from 4 to 1; conditions on interior surfaces worse by (0.5 to 2 points) over traffic.
- Chloride testing on WF diaphragm near east abutment measured 0 ppm chlorides beneath joint opening.
- Chloride tests over the northbound right shoulder on interior girder ranged from 3 ppm on the web to 18 ppm on the bottom of the bottom flange.
- Core taken from diaphragm web over northbound right shoulder; Index = 3, (3 ppm chlorides measured).
- Chloride tests tended to have minor leakage issues due to the condition of the patina surface and cold ambient temperatures during the inspection.

Figure 1. Exterior surfaces over traffic in good condition after more than 40 years.

Figure 2. Interior surfaces over traffic showing signs of long-term deterioration.

Figure 3. Interior surfaces near east abutment with less deterioration than areas over traffic.

Figure 4. East pier viewed from east abutment. Drainage deflectors separating spans effectively.

Figure 5. Heavy flaking of bottom of flange in traffic span, typically Index = 2 or worse.

Figure 6. Flaking and delamination of bottom of flange on interior half of fascia girder over southbound lanes.

FM R-75 over I-35	**9951.4O035**
NBI Structure No. 602615	
	MAP ID: 12
	FACILITY CARRIED: FM R-75
	FEATURES CROSSED: I-35
	COUNTY: 099 - Wright
	LOCATION: At Junction R-75
	LATITUDE: 42.57287356
	LONGITUDE: -93.54845939
	YEAR BUILT: 1971
	VERTICAL UNDER CLEARANCE: 16'-11"
	AADT UNDER (ESTIMATED): 14,600
	% TRUCKS UNDER (ESTIMATED): 24%

STRUCTURE DESCRIPTION:

Four continuous plate girders over four spans. Conventional abutments with skew of approximately 45°. Cross-frames between girders are single angle diagonals with a WT bottom member. Drainage deflector plates only installed on exterior fascia flanges; water can migrate on interior from span to span. WT lateral bracing between middle interior girders in main spans over roadway. No lateral bracing in abutment spans. Sloped embankments.

SUMMARY OF CONDITION:

- Patina in good condition considering over 40 years of service; however, interior horizontal surfaces (top and bottom) directly over traffic lanes showing signs of more substantial deterioration.
- Index typically = 3.5 on all fascia or other exposed surfaces, whether over traffic or near abutments. Index rating = 3 for interior surfaces near abutments (even tops of bottom flanges, which show moderate poultice but no real flaking), Index = 2 or worse for all interior surfaces over traffic.
- Concrete deck in good condition and light traffic above means virtually all salts and water come from below.
- Direct salty spray from high-speed truck traffic over time likely driving deterioration over traffic lanes.

TESTING PERFORMED:

- Visual inspection from ground.

Figure 1. Overall appearance of north end of bridge showing high skew.

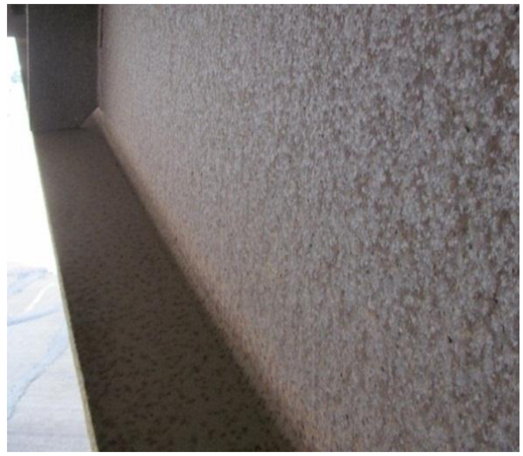

Figure 2. Typical interior web and top of bottom flange near south abutment; poultice not flaking. Index for both surfaces is 3.

Figure 3. West fascia girder exterior; Index = 3.5 after over 40 years of service.

Figure 4. Typical cross frame condition near south abutment. Index = 3.

Figure 5. Heavy flaking visible from the ground on interior flanges and webs over traffic lanes; Index = 2.

Figure 6. Center bay viewed over top of south pier; note lack of deflector plates and concrete staining.

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APPENDIX D — CHLORIDE TESTING AND LAB RESULTS

INTEROFFICE MEMORANDUM

Via: Project Folder

To: Douglas Crampton

From: Kimberly A. Steiner

Date: December 13, 2012

Project: Iowa Weathering Steel Bridges
WJE No. 2011.1671

Subject: Water-soluble chloride and sulfate analyses

Water-soluble chloride contents were measured on five samples of steel removed from weathering steel bridges in Iowa. Each sample consisted of a core of steel. The cores were cut in half axially to separate the two faces, so that the chloride measured could be related to the face tested. For each sample, only one face was tested, which corresponded to the surface where field chloride testing was performed.

The samples were extracted essentially according to the SSPC-Guide 15 Field Methods for Retrieval and Analysis of Soluble Salts on Steel and Other Nonporous Substrates boiling extraction method. The samples were immersed in deionized water and boiled for one hour. The extract was cooled, decanted, and brought to a consistent volume for each sample. Chloride content was measured by titration with silver nitrate as described in ASTM C 1218, *Test Method for Water-Soluble Chloride in Mortar and Concrete*. Results are provided in Table D-1.

The extracts with the highest and lowest water-soluble chloride contents were also tested for water-soluble sulfate using a turbidimetric technique where the extract is mixed with barium chloride to form insoluble barium sulfate. The concentration of sulfate is measured using visible light spectroscopy. The results are presented in Table D-1.

Table D-1. Chloride and Sulfate Contents.

Sample	Water-soluble chloride (μg/cm_2)	Water-soluble sulfate (μg/cm_2)	Field-measured chloride* (μg/cm_2)	Extraction Efficiency*
FS4	407	293	30	7.4%
FS5	313	--	35	11.2%
FS7 - Over	107	--	6	5.6%
FS7 - Under	33	70	1	3.0%
FS11	172	--	3	1.7%

*Using CHLOR*TEST sleeves

APPENDIX E — SEM/EDS, FTIR, AND XRD LAB TEST RESULTS

INTEROFFICE MEMORANDUM

Via: Project Folder

To: Douglas Crampton

From: Kimberly A. Steiner

Date: December 14, 2012

Project: Iowa Weathering Steel Bridges
WJE No. 2011.1671

Subject: Laboratory analyses of corrosion product

Three samples of corroded weathering steel cores removed from bridges in Iowa were selected for laboratory study of the corrosion product. These studies were undertaken to determine if compositional analysis using laboratory techniques could provide useful information regarding the protectiveness of the patina on the steel. Literature research has indicated that laboratory testing of the corrosion product on the steel can provide information regarding the protectiveness of the patina. Not all patinas on weathering steel are protective; the development of the patina depends on many factors, including age, number and duration of wet/dry cycles, atmospheric humidity, and the presence of corrosion accelerators such as chloride and atmospheric pollutants. In the case of bridges in Iowa, the primary anticipated corrosion accelerator is chloride from deicing salts used during winter months.

The corrosion products present on weathering steel structures contain many different phases, which result from the interaction of the steel and the environment. The corrosion product on weathering steel structures may contain goethite (α-FeOOH), akagenite (β-FeOOH), lepidocrocite (γ-FeOOH), magnetite (Fe_3O_4), hematite (Fe_2O_3), maghemite (γ-Fe_2O_3), and others. Each phase has been correlated with a greater or lesser degree of corrosion protection. Goethite, particularly nanocrystalline and/or chromium-containing goethite, is considered particularly protective. Akagenite, lepidocrocite, maghemite and magnetite are considered less protective. Akagenite can readily incorporate chloride ions in its crystal structure, and has been found to be present in greater quantities in corrosion products of weathering steel in high chloride environments.

The literature describes analysis of weathering steel corrosion products using several different techniques, three of which were selected for use in this study. The techniques used were: scanning electron microscopy with energy dispersive x-ray spectroscopy (SEM/EDS), Fourier transform infrared spectroscopy (FTIR), and x-ray diffraction (XRD). The samples selected for study were: FS4, FS7-Under and FS7-Over. Each sample had been cut in half longitudinally, so that only one face of the core was available for examination. Each sample represents the opposite face of the core used for chloride and sulfate testing (described in a separate memo).

SEM/EDS

In SEM, a beam of electrons is generated, focused, and scanned across a very small area of the sample. The electrons interact with the sample in many ways, which can be used to image and analyze the sample.

Two imaging modes are possible: backscattered and secondary. During backscattered electron (BE) imaging, the electron beam bombards the sample, and some electrons are backscattered or elastically scattered by the elements in the sample based on their atomic number. Heavier atoms in the sample scatter the beam electrons more than lighter atoms; hence phases with a higher average atomic weight appear brighter in the resulting image than phases with a lower average atomic weight, providing compositional information within the image. Secondary electron (SE) imaging uses electrons that are emitted from the sample as a result of inelastic interactions with the beam. SE images provide information related to the topography of the specimen; cracks and crystals deposited on the surface will be well defined. The interaction of beam electrons with the sample also generates characteristic x-rays. The energy of the characteristic x-rays can be measured using an EDS, and the elements present in the sample can be identified. EDS can only identify elements heavier than boron (carbon through uranium); therefore lighter elements, such as hydrogen, do not appear in the spectrum. EDS data can be collected from a point a few microns across, or over a larger area of the sample.

SEM/EDS was used to determine the elemental composition of the corrosion product. The EDS provides information about chemical elements present in a sample, but does not indicate the ways in which the elements are combined to form compounds.

For all three samples examined, iron and oxygen were the primary elements present in the corrosion product. Sulfur was typically present in low quantities. Chlorine was present in some areas, but was not present in all areas examined. The low peak intensity of the chlorine indicates that the chlorine is present in low quantities. With the SEM, EDS data can be collected over a relatively large area (square millimeters), or the probe can be focused on a small area. Even when focused on a small area, the chlorine and sulfur contents remained low, indicating that these elements, and the compounds in which they are contained, are not concentrated in certain areas of the corrosion product.

In addition to iron, oxygen, sulfur and chlorine detected by EDS, minor amounts of manganese, chromium, calcium, silicon and sodium were also frequently observed in the spectra. Manganese and chromium are components of the underlying weathering steel, and are considered to have been incorporated into the corrosion product. Silicon is present in the alloy, but is also present in the environment, and may have originated from the underlying steel or may be present as atmospheric deposits (debris) on the surface that became incorporated into the corrosion product. Calcium is a primary component of concrete, and is believed to represent debris that became incorporated into the corrosion product. Sodium may be present from exposure to sodium chloride deicing salts.

It is noteworthy that the chloride levels observed with SEM/EDS were similar in all three samples; this contrasts with chloride tests performed on the other halves of the core specimens. The chloride test data showed a four-to ten-fold difference in chloride content between FS4 and the FS7 samples, with FS4 having the greater concentration. In the case of the FS4 sample selected for chloride testing, the core surface that had been facing upward while in service (and the more likely surface for chloride deposition) was selected for chloride testing, while the opposite face (downward) was selected for SEM/EDS. The water-soluble chloride content of the downward face was not tested, but can be reasonably assumed to be substantially lower than the upward face. This may explain the absence of significant differences in chloride contents between FS4 and the FS7 samples by SEM/EDS.

Images and EDS spectra from the samples are provided in Figures E-1 through E-4.

FTIR

Fourier transform infrared spectroscopy (FTIR) is a type of molecular spectroscopy that is used to determine the types of compounds present in a system. During FTIR analysis, infrared radiation is passed through the sample or reflected off of the sample. The radiation is absorbed by chemical bonds in the sample being analyzed. Each type of bond absorbs radiation at a particular wavelength (frequency). The type of chemical bonds present in the sample can therefore be determined by the peaks indicating absorption at a particular wavelength. The spectrum (graph) consists of a series of peaks showing increased absorption (or decreased transmission) of radiation at certain wavelengths. The x-axis on the graph is typically given as wavenumbers (cm^{-1}), which is the inverse of the wavelength in centimeters.

FTIR, unlike SEM/EDS, can be used to identify compounds present in a sample. However, unlike SEM/EDS, the FTIR cannot detect small quantities of other elements (such as sulfur and chlorine) that may be present in small quantities in the compounds. Also, not all compounds of interest have significant patterns in the mid-infrared regions used for the analysis, so some of the compounds likely present, such as hematite and magnetite, are difficult to detect by FTIR in the presence of other compounds. In addition, FTIR is generally not suitable for identifying compounds present in small quantities of a mixed system such as a corrosion product, because the spectrum is overwhelmed by the data from the compounds in larger quantities.

FTIR analyses were performed for Samples FS4 and FS7-Under. The spectra, shown in Figure E-5, looked essentially the same. Significant peaks correlating with goethite and lepidocrocite have been identified. A very minor peak (actually a weak shoulder on a descending base line) was also present, which may be associated with a low intensity signal from akagenite.

XRD

XRD analysis is suitable for identifying crystalline compounds; non-crystalline compounds do not have a definite XRD pattern. During x-ray diffraction analysis, radiation produced from an x-ray source is diffracted off the sample at various angles. A detector measures the intensity of the diffracted energy, and the location (angle) and intensity are recorded as a graph. This graph, which displays a pattern of peaks, can be interpreted to identify the crystalline components of the sample. The peaks are compared to a library of diffraction patterns of known components.

XRD analysis was performed on Sample FS4. No crystalline components were detected. Most likely, the compounds detected by FTIR are present in either poorly crystalline or nanocrystalline forms that are difficult to detect using XRD analysis.

Figures

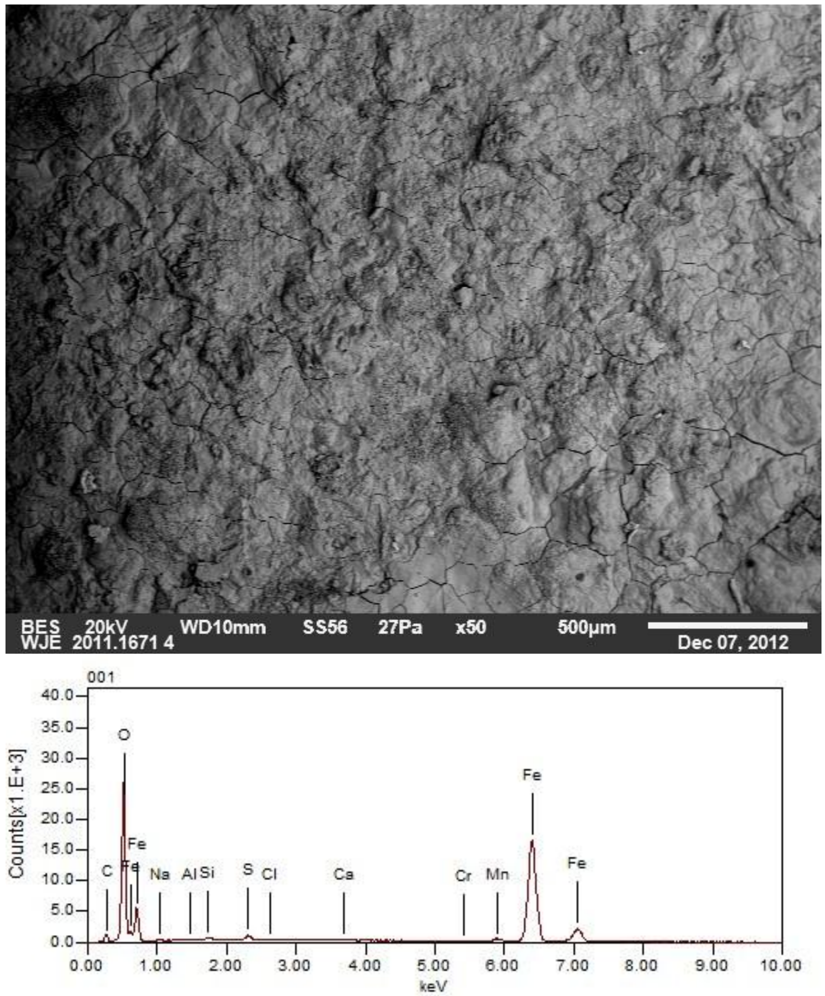

Figure E-1. BE micrograph and area EDS spectrum of the surface of Sample FS4.

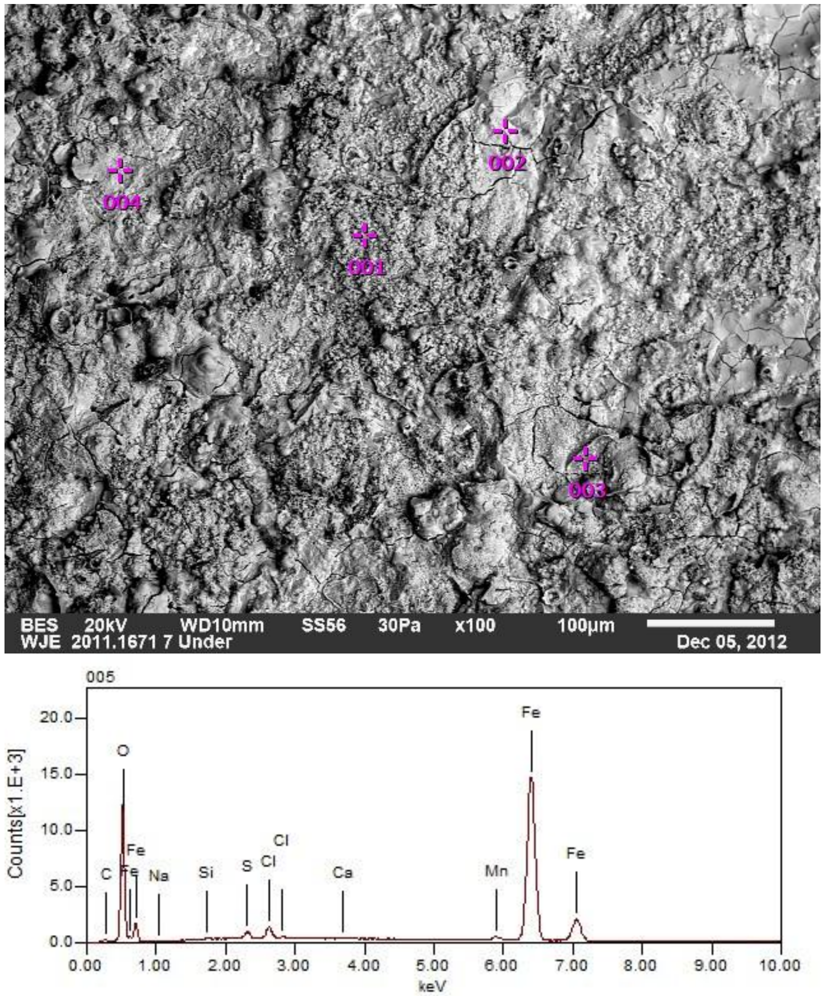

Figure E-2. BE micrograph and point EDS spectrum from the surface of Sample FS7-Over. The EDS spectrum presented is from point 005, and represents the general composition of the area imaged.

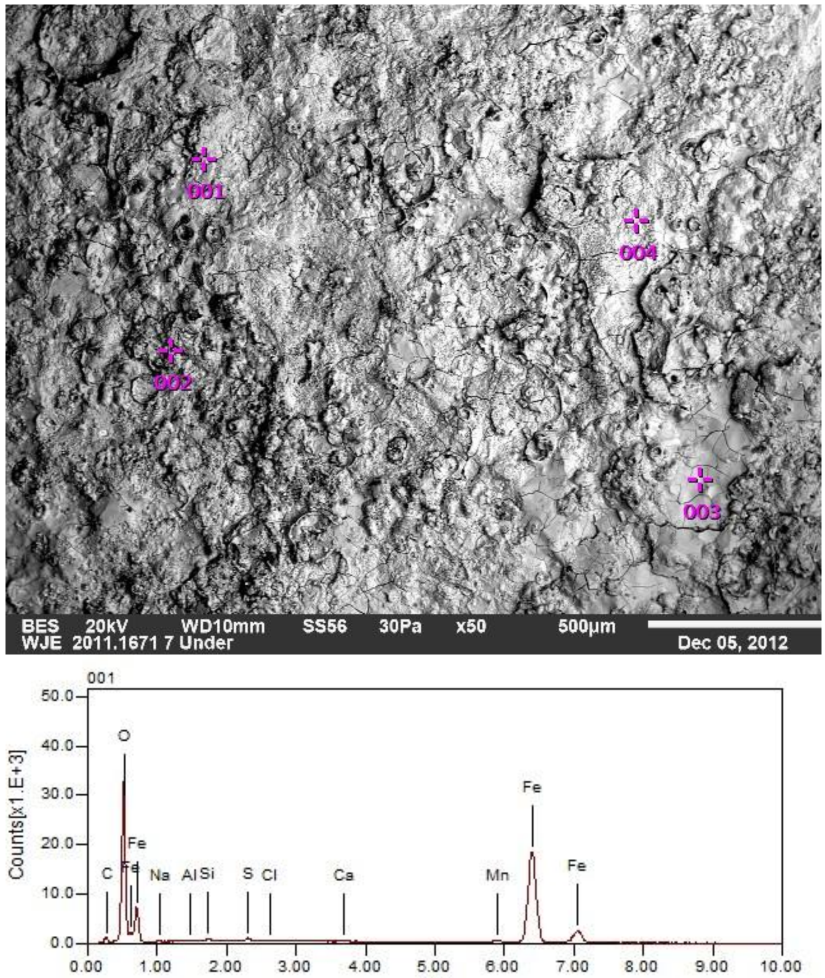

Figure E-3. BE micrograph and point EDS spectrum from the surface of Sample FS7-Under. The EDS spectrum presented is from point 001, and represents the general composition of the area imaged.

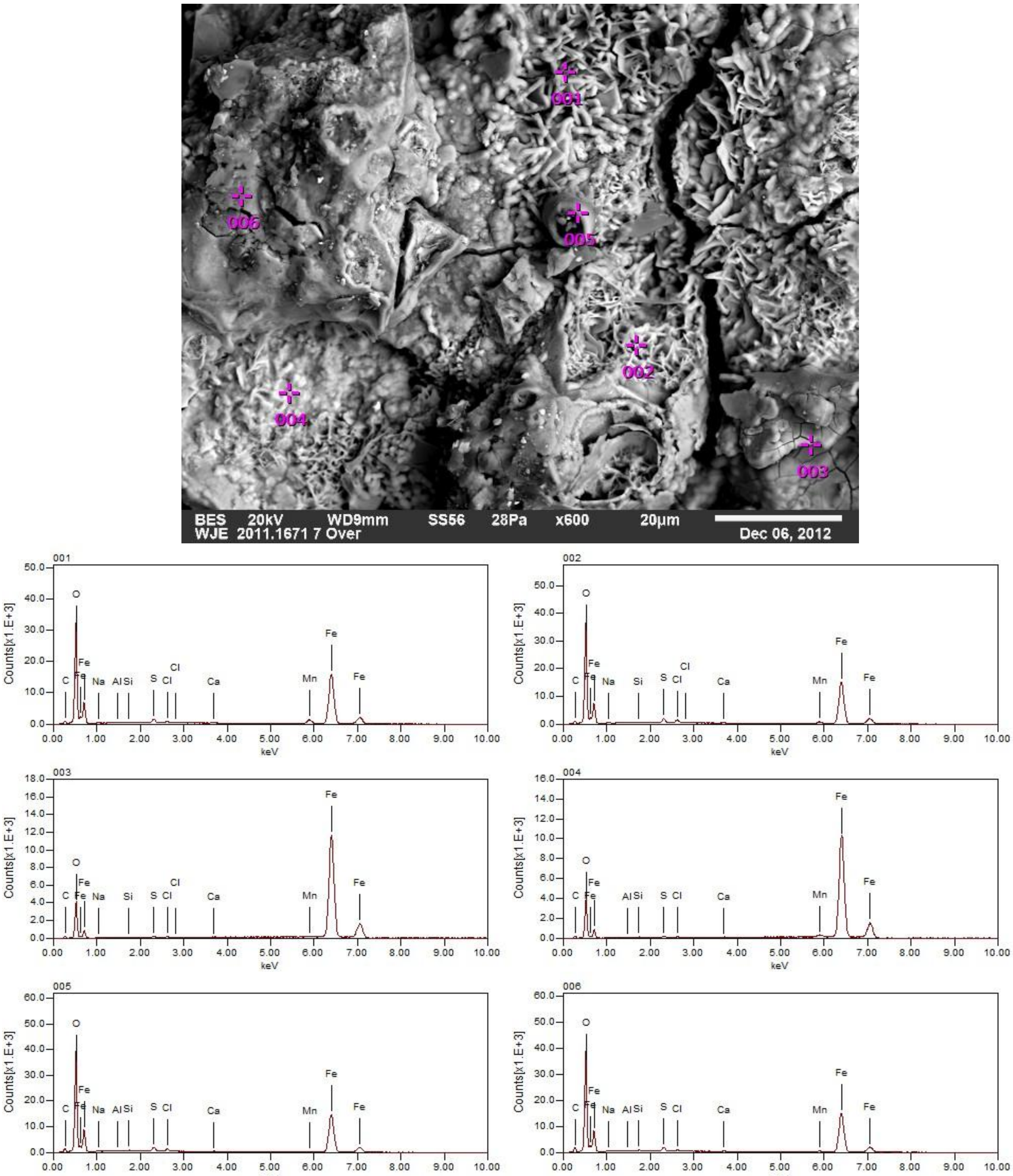

Figure E-4. BE micrograph and point EDS spectra from the surface of Sample FS7-Over. Each EDS spectrum corresponds to a point indicated on the micrograph. The number in the upper left corner of the EDS spectrum correlates to the number on the micrograph.

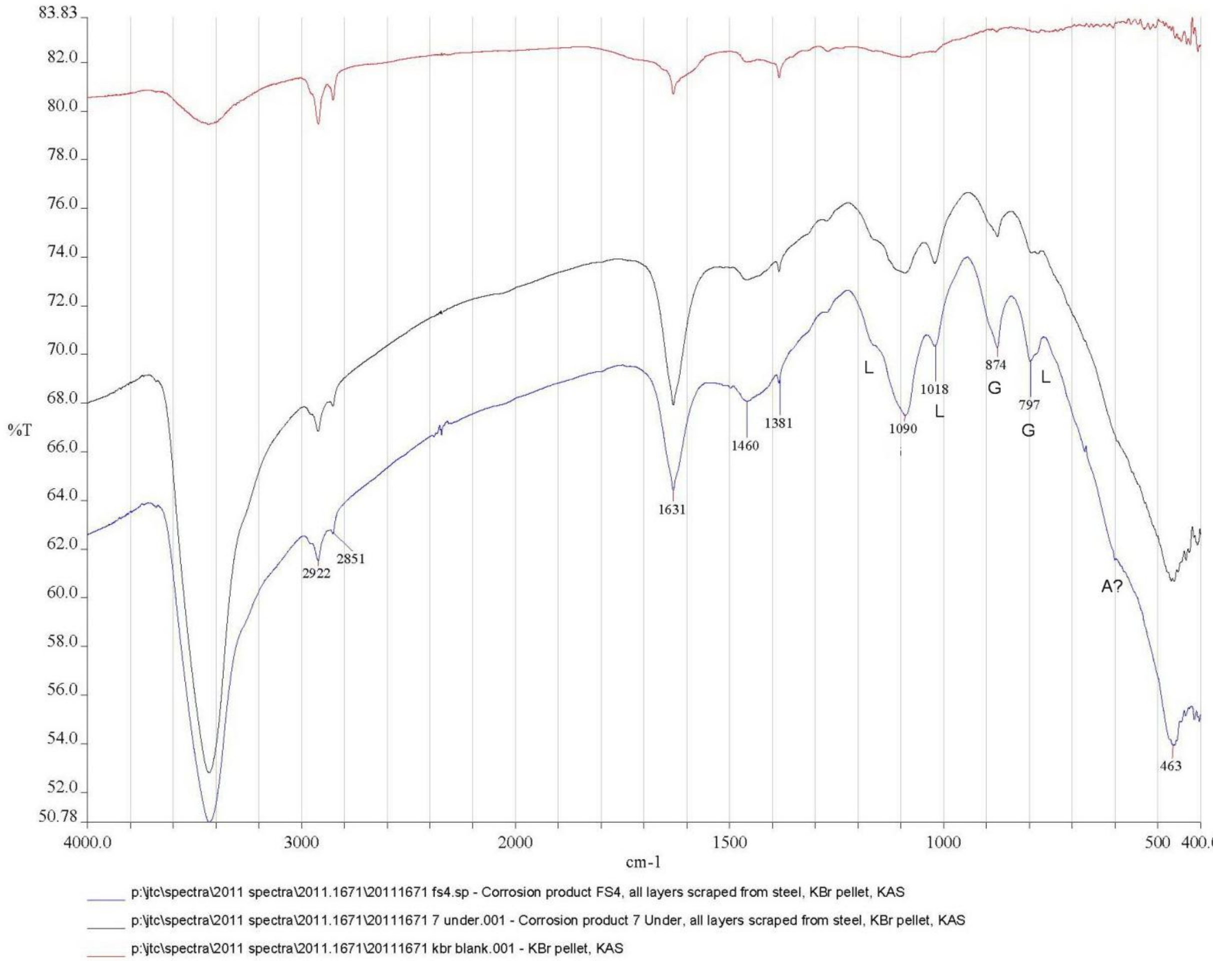

Figure E-5. FTIR spectra of Sample FS4 (bottom line), Sample FS 7-Under (middle line) and a blank (top line). Peaks correlating to goethite are marked with a "G," peaks correlating to lepidocrocite are marked with an "L," and a peak tentatively identified as correlating with akagenite is marked with an "A?."

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APPENDIX F — PROPOSED FIELD INSPECTION RATINGS

Table F-1. Proposed Patina Evaluation Rating Scale

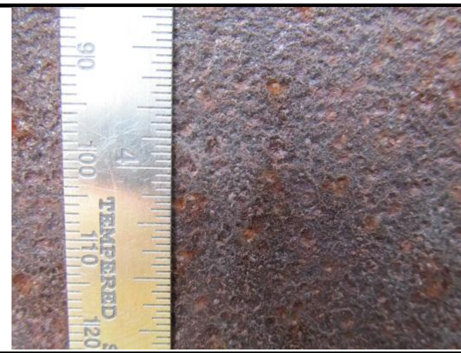
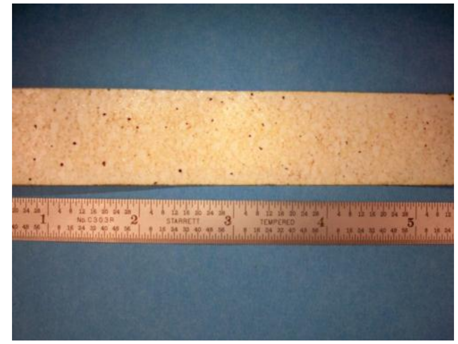
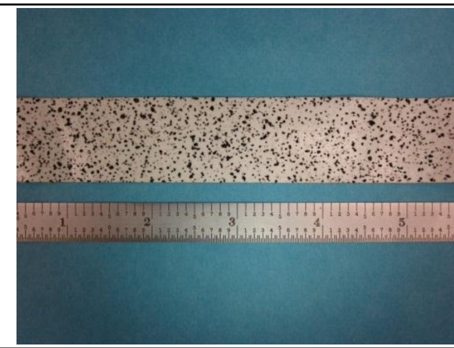
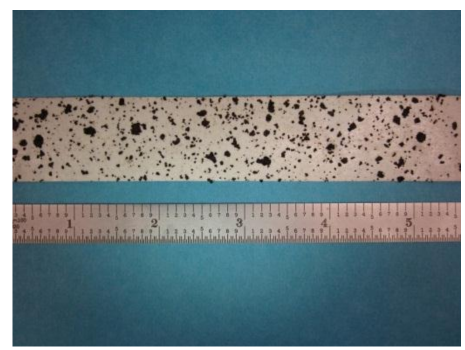
Patina Rating	Condition Description	Example Condition in Field	Example Tape Test Specimen
8 Very Good	Uniform color pattern, generally dark brown with some lighter reddish-brown, metallic and purple-brown spots. May be difficult to see small rust product clusters. Texture may be dimpled or rough but uniform in pattern. Patina layer is thin but dense and very adherent, indicative of very good protective properties. Superior adherence; tape test sparse with only very small flakes (< 1 mm).		
7 Good	Uniform color pattern, generally dark brown with some lighter reddish-brown, metallic and purple-brown spots. Individual rust product clusters visible. Texture is dimpled or rough but uniform in pattern. Patina layer is thin but dense and adherent, indicative of good protective properties. Tape test easily removes very small (< 1 mm) flakes.		
6 Satisfactory	Dark brown coloration, but begins to show minor variation. 1-5 mm flakes loose on surface, easily removed with tape test. Underlying layer adherent, still relatively dense, thin and protective. Texture more granular and loose flakes may be less-protective, holding water and salts. Chalky poultice layer may be present, but not significantly affecting performance (i.e., flake size).		

Table F-1. Proposed Patina Evaluation Rating Scale (continued)

Patina Rating	Condition Description	Example Condition in Field	Example Tape Test Specimen
5 Fair	Dark brown with black and some color variation. Blotchy with some salty or rusty stains. Medium (5-25 mm) flakes over most of area loose and non-protective, easily removed with tape test. Layer beneath flakes thicker and more permeable, with some pitting beginning. Non-protective; contaminants penetrating. Elements with poultice may show significant associated flaking.		
4 Poor	Color is dark brown and black but non-uniform, with widespread blotchiness and staining. Non-protective. Large (> 25 mm) flakes, or layered delamination beginning in some areas. Thickness/permeability of rust increased, with pitting and section loss possible. Poultice areas have thin delamination sheets or very large flakes. Layer below loose poultice may appear similar, but still somewhat adherent.		
3 Serious	Blackish, stained, blotchy appearance. Formation of laminar sheets with deeply pitted semi-adherent layer beneath; chunks and sheets of rust product removable by hand. Aggressive advancement of pitting and section loss; can be up to 50%. Complete failure of patina to protect base steel.