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Investigation of Painted Steel Piles at a Marine Commerce Terminal in Coastal New England

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ABSTRACT

This case study presents the results and conclusions of an investigation of painted steel piles at a marine commerce terminal in coastal New England, including a review of relevant engineering specifications and other documents, an on-site field investigation, and laboratory analysis of samples collected. A review of specifications showed that the specifications approved for the paint system were inadequate for long term service without using cathodic protection. No cathodic protection was placed on the back side of piles and should be extended to back side for corrosive soil exposure. After five years, the paint coating looks good in non-repaired areas. No corrosion or blisters were observed in non-repaired areas in the atmospheric zone or in areas where there is no mechanical damage or barnacles. Maintenance/repair coating of the previously repaired and mechanically damaged areas and cathodic protection monitoring can take care of problems. No corrosion or accelerated corrosion in blisters was observed due to cathodic protection and high pH. Indications are that barnacles contributed and may have caused the blisters.

Key words: marine corrosion, coatings, blistering, cathodic protection,

INTRODUCTION

At the request of a fabricator and coater of steel pipe and structural members, the authors undertook an investigation of painted steel piles at a marine commerce terminal in coastal New England. This company was concerned when the owners suspected a potential corrosion problem with the steel piles, and we were asked to perform the investigation. The investigation included a review of relevant engineering specifications and other documents, an on-site field investigation, and laboratory analysis of samples collected.

REVIEW OF ENGINEERING SPECIFICATION AND OTHER DOCUMENTS

The following engineering specification and other documents were reviewed as part of this study.

- Engineering specification for marine commerce terminal, steel sheet piling.
- Seventeen (17) fabrication and coating shop drawings.
- Engineering submittal cover sheet and contractor approval for fabrication and coating shop drawings.
- Facility usage plan for marine commerce terminal,

Comments Concerning the Engineering Specification

The fabricator and coating applicator prepared the surface in accordance with the specifications, which included the following.

- Shop surface preparation per the Steel Structures Painting Council (SSPC)[(1)] SSPC-SP1, Solvent Cleaning and SSPC-SP 10, Near-White Metal Blasting.
- Shop coating with two (2) coats of epoxy conforming to SSPC-Paint 16.
- Apply primer coat and two (2) coats of paint having a total of 12 mils dry film thickness. The coating shall be applied to both sides of all sheets except for those specifically noted on plans as being uncoated.

The specifications did not require checking the surface for non-visible contamination prior to painting and limited the specification to cleaning procedures based on visual inspection, as are the procedures described by SSPC-SP 1, Solvent Cleaning and SSPC-SP 10, Near-White Metal Blasting. The engineering specification should have documented more detailed QA/QC procedures to identify potential surface contaminants.

Coating selection by the project owner and their engineering representative as given in the specifications did not consider biological growths such as barnacles and its effect on the coating. The epoxy coating used does not protect against biological growth, or biofouling. This was the wrong coating system for an application and exposure that biological growth results in the damage of the coating. In this application, an antifouling top coating should have been specified as a third coat to prevent biological growths.

The specifications did not specify cathodic protection and potential criteria for corrosion mitigation until four years after construction. The engineering specification should also have specified cathodic protection and potentials in the -0.85 to -0.95 volt range.

Comments Concerning the Drawings and the Engineering Approval

All seventeen of the fabrication and coating shop drawings contained the following specification with regard to painting.

- Clean to SSPC-SP 10
- Coat 12 mils dry film thickness epoxy coating.

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[1] Steel Structures Painting Council, 40, 24th Street, Suite 600, Pittsburgh PA 15235.

All parties, including the project owner and their engineering representative agreed with both the engineering specifications and the fabrication and coating shop drawings.

Comments Concerning the Facility Usage Plan

The facility usage plan for the marine commerce terminal has an important note number 4 which will be discussed here. There are five specified actions to be taken by the owner of the facility in order to maintain the ability of the facility to support the specified loading conditions over the life of the facility, which is estimated to be 50 years. The five actions to be taken by the owner are as follows.

- Documented yearly inspections of the steel sheeting and pilings.
- Re-coating of the steel sheeting and pilings every 5-10 years post-construction, based upon results of yearly inspections.
- Documented yearly evaluation of the need for an impressed cathodic protection system beginning 5 years post-construction.
- Installation of an impressed cathodic protection system not more than 15 years post-construction, unless yearly inspections note its necessity before that time.
- Documented yearly evaluation of the loading capacity of the facility beginning 30 years post-construction.

Bullet point number two implies that the engineering firm for the project understood that the coating would degrade naturally over time, and their technical judgement was that service life of the coating in this environment would not exceed 10 years.

With regard to bullet point three concerning the evaluation of the need for impressed cathodic protection after year five, it is important to note that the owner actually had an impressed cathodic protection system installed before 5 years post-construction. On-site inspection and photographic documentation show that the steel surface under the coating blisters is free from corrosion or accelerated corrosion. Passive film can be clearly seen. This shows that the installed impressed cathodic protection system protects the steel from corrosion attack

Summary of Findings

The following is a summary of findings of the engineering specification and other documents.

- Surface preparation was performed per specifications by fabricator and coating applicator. However, the paint specification was inadequate. The specifications did not require checking the surface for contamination prior to painting and limited the specification to cleaning procedures based on visual inspection; as are the cleaning procedures SSPC-SP 1, Solvent Cleaning and SSPC-SP 10, Near-White Metal Blasting.
- Facility usage plan considered cathodic protection but planned to put in service after 5 – 15 years in service instead of installing right away. In the nature of coating, owner and user understood the nature of coating that it requires ongoing inspection and routine repair and maintenance.
- All parties, including the project owner and their engineering representative agreed with both the engineering specifications and the fabrication and coating shop drawings.
- Coating selection by the project owner and their engineering representative did not consider biological growths such as barnacles and its effect on the coating. Anti-fouling top coat should

have considered for the portions of the sheet piles being submerged in sea water and exposed to barnacle growth.

ON-SITE INVESTIGATION

The itinerary for the two-day investigation was conducted as follows.

- Measured coating thicknesses and wall thicknesses for piles 9, 11, and 13.
- Collected potential data at piles 9, 11, and 13.
- Collected coating samples at pile 13 from good areas, recoated areas, and coating delamination/cracked areas.
- Glued dollies and performed tensile adhesion testing on pile 13 and pile 11.
- Conducted potential survey from pile 13 to pile 10 (2^{nd} bumper).
- Collected coating samples from the blisters.
- Collected liquid samples under the blisters, but the samples were too small for analysis.
- Collected ocean water from five locations.
- Removed barnacles from piles by scraping (selected more than 10 plates randomly) and observed blistering under barnacles on every plate. Observed black spots (could be magnetite) under the blisters.

Coating Thickness, Wall Thickness and Potential Measurements

A wall thickness gauge was used for measuring wall thickness of the piles. A coating thickness gauge was used for measuring the coating thickness of the piles. Potential measurements were made at various depths in one-foot increments on the surface of the piles using a silver/silver chloride (Ag/AgCl) reference electrode.

On pile 13, plate 77, coating thickness range from a low of 0.60 mil at the repair patch/splash zone to as much as 21.1 mils in the high tidal zone. In the shop coated high tidal and low tidal zones, the coating thickness ranged from 10.3 to 21.1 mils. Wall thickness ranged between 0.490 and 0.558 inch in the corroded area and between 0.506 and 0.529 inch in the good (not corroded area). Potential measurements increased from -1.03 at one foot below water surface to the approximate range -0.95 to -0.96 volts between two and ten feet depth, and then increased rapidly to -1.46 volts at 12 feet depth.

On pile 11, plate 76, coating thickness range from a low of 16.2 mils at the low tidal zone to as much as 45.6 mils in the repair patch/splash zone. In the shop coated high tidal and low tidal zones, the coating thickness ranged from 16.2 to 27.2 mils. Wall thickness ranged between 0.543 and 0.552 inch in the high tidal zone and between 0.540 and 0.546 in the low tidal zone. Potential measurements decreased from -1.06 volts at one foot below water surface to -1.08 volts at ten feet depth.

There was no evidence of blisters on plates 75 – 81 of pile 11. Coating color is different compared to pile 13. The difference in color could be due to UV degradation of coating on pile 13. There was no evidence of pitting. However, there were indications of corrosion at the coating repair/mechanical damage areas.

On pile 9, plate 87, coating thickness range from a low of 13.3 mils at the low tidal zone to as much as 33.0 mils in the repair patch/splash zone. In the shop coated high tidal and low tidal zones, the coating thickness ranged from 13.3 to 25.7 mils. Wall thickness ranged between 0.534 and 0.542 inch in the high tidal zone and between 0.543 and 0.558 in the low tidal zone. Potential measurements decreased slightly from -1.07 volts at one foot below water surface to -1.076 volts at 12 feet depth.

There was no of blisters on the examined plates 87 – 92 of pile 09. In the examined area, a carbon steel (CS) plate was welded to the pile and anode cables is welded to the CS plate. One more small CS section was attached to the pile to support PVC pipe that carries anode cables. There was no evidence of pitting. However, there were indications of corrosion at the coating repair/mechanical damage areas. evidence

Photographic Documentation

Figure 1 is a photograph of Pile 13 showing that mill coating was damaged and recoating was applied on-site at the damaged areas. The mechanical damage noticed on alternate plates is of similar pattern and present at similar position. Figure 2 is a photograph of Pile 13 showing mechanical damage areas in the splash zone, epoxy putty repairs at some of the corroded areas in the high tidal zone and barnacles in the low tidal zone.

Figure 3 is a photograph of Pile 13 showing the locations of adhesion test. Figure 4 is a photograph of Pile 13 showing cracks in the coating and corrosion deposits underneath the coating. Figure 5 shows a closer view of Figure 16 after removing the coating and corrosion deposits.

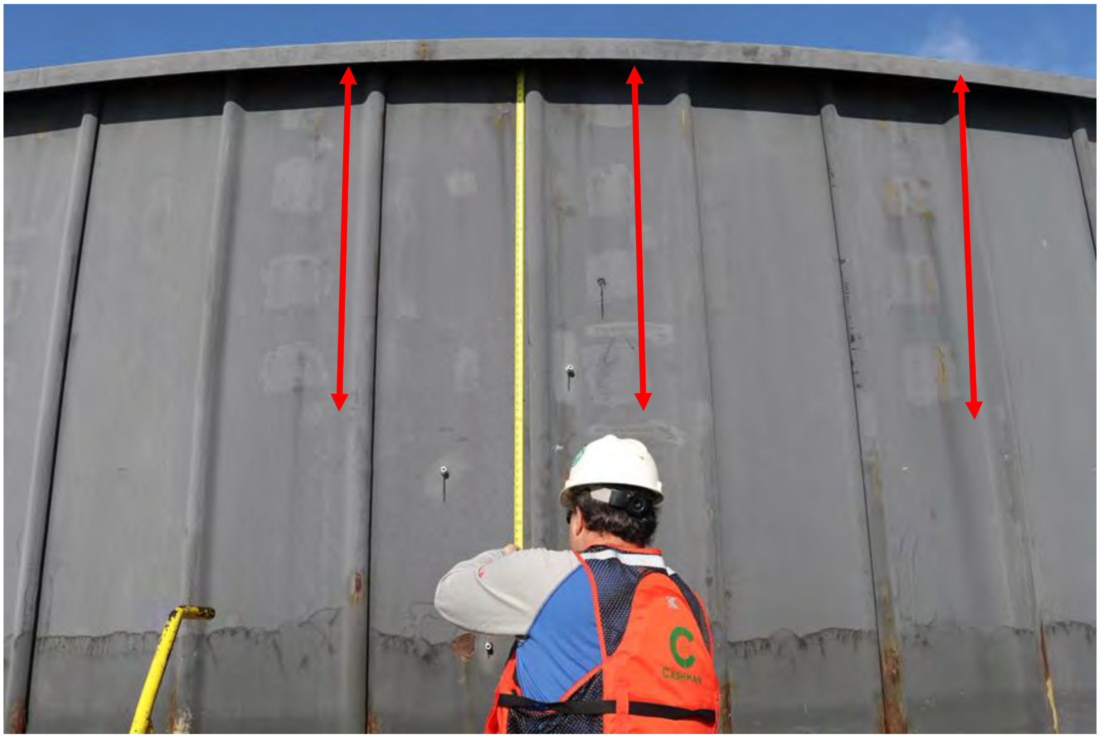

Figure 1: Photograph of Pile 13 showing that mill coating was damaged and recoating was applied on-site at the damaged areas. The mechanical damage noticed on alternate plates is of similar pattern and present at similar position.

Figure 2: Photograph of Pile 13 showing mechanical damage areas in the splash zone, epoxy putty repairs at some of the corroded areas in the high tidal zone and barnacles in the low tidal zone.

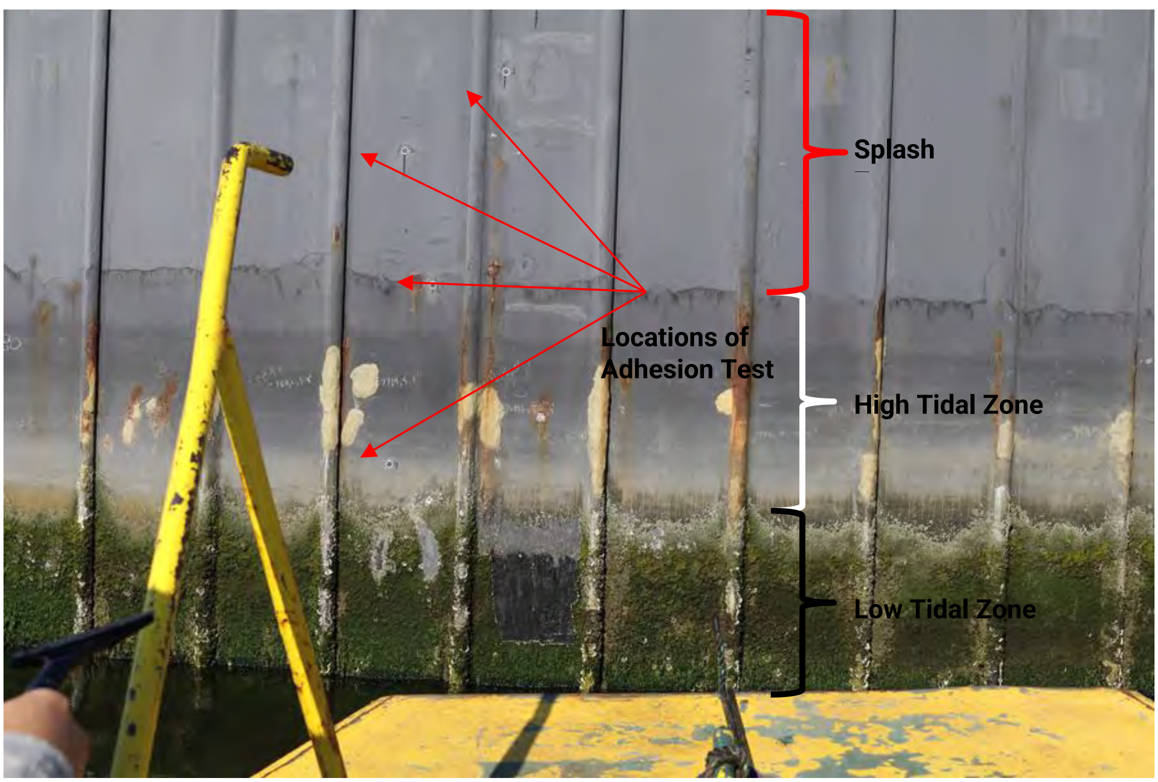

Figure 3: Photograph of Pile 13 showing the locations of adhesion test.

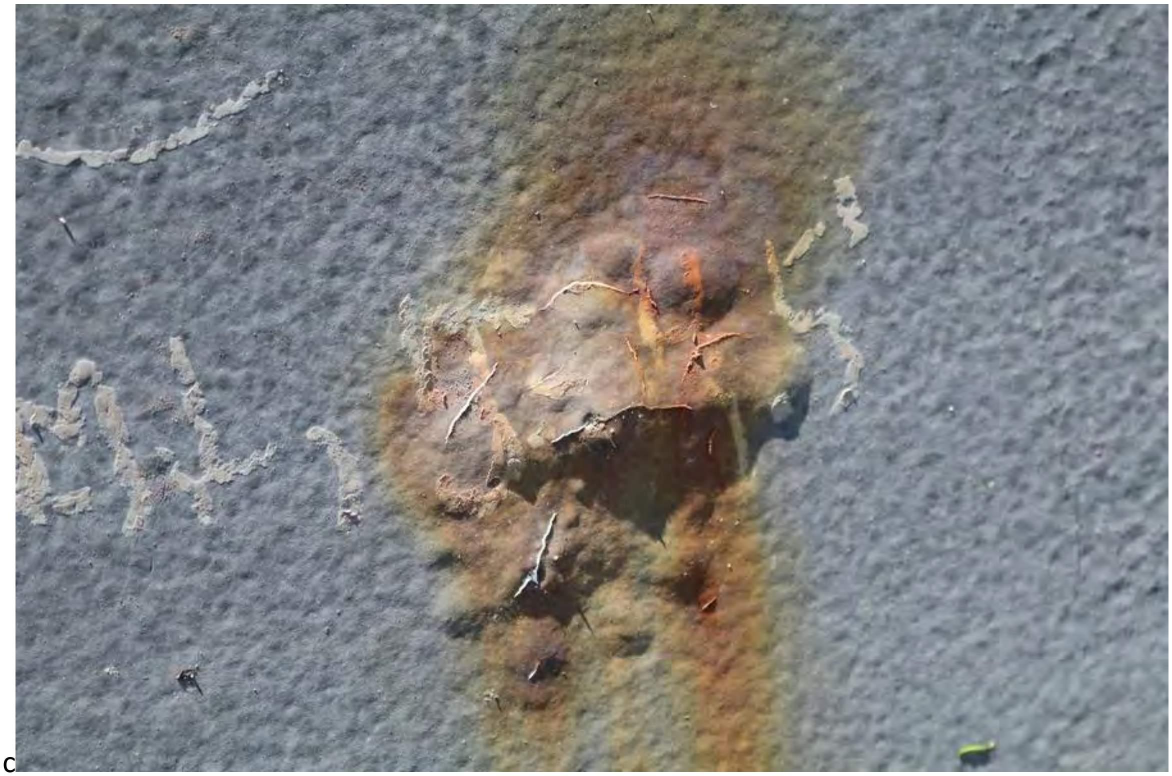

Figure 4: Photograph of Pile 13 showing cracks in the coating and corrosion deposits underneath the coating.

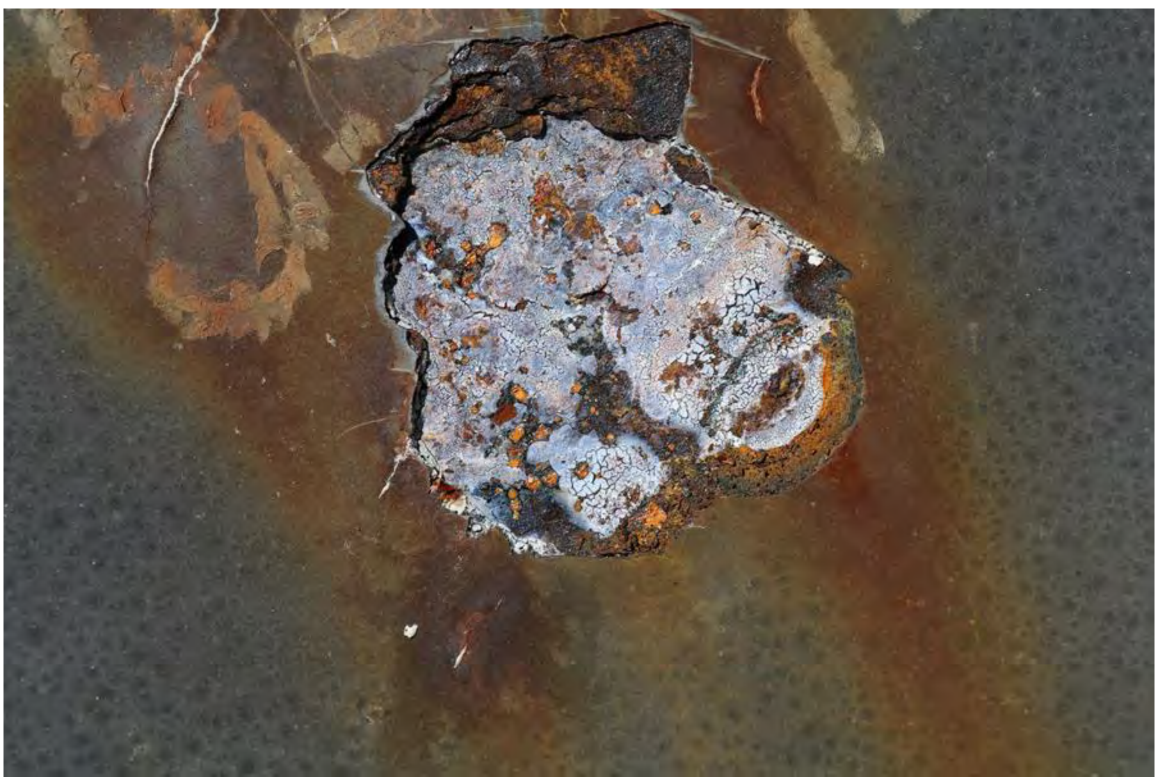

Figure 5: Closer view of Figure 4 after removing the coating and corrosion deposits.

Examination of Coating Blistering Under Barnacles

Coating blistering under scraped barnacles was examined closely and extensively documented by photographs. Figures 6 and 7 present photographs showing blisters in the coating after the barnacles in the low tidal zone are removed by scraping. Blisters in the coating are restricted only to low tidal zone and below under the barnacles which suggests existence of fouling activity.

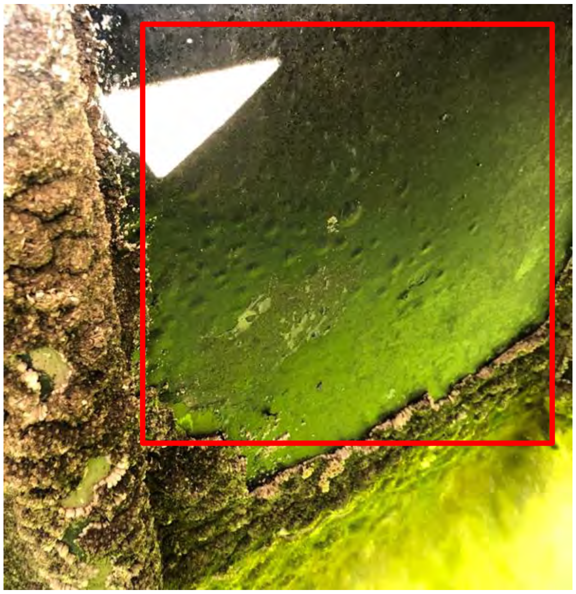

Figure 6: Photograph showing blisters in the coating after the Barnacles in the low tidal zone are removed by scraping. No evidence of blisters in the coating in the high tidal zone which is free from barnacles.

Figure 7: Photograph showing blisters in the coating after the barnacles in the low tidal zone are removed by scraping. No evidence of blisters in the coating in the high tidal zone which is free from barnacles.

Figure 8 is a photograph showing that the steel surface under the coating blisters is free from accelerated corrosion. Magnetite (black spots) can be clearly seen. Magnetite is a protective form of iron oxide (Fe_3O_4) and serves as a passivating film on the steel surface.

Figure 8: Photograph showing that the steel surface under the coating blisters is free from accelerated corrosion. Magnetite (black spots) can be clearly seen.

Tensile Adhesion Testing

Tensile adhesion testing on four separate locations in the high tidal zone of Pile 13. The tensile adhesion test results for dollies one through four were as follows: 2600 psi, 2600 psi, 1500 psi, 1300 psi. The residual coating attached to the dollies after adhesion testing were returned to the laboratory for SEM/EDS analysis.

Summary of Findings

The important findings of the on-site investigation were the following.

- Painted piles meet the specification thickness requirements of 12 mils in non-repaired areas.
- Painted surfaces have adequate adhesion in non-repaired areas – 1300 psi to 2600 psi in the high tidal zone of Pile 13. Two-layer paint application does not make any difference after 5 years. Barrier effect is the same and adhesion remains the same and adequate after 5 years exposure in non-repaired areas.
- Painted surfaces exhibit blistering mostly under barnacles. Most of the blisters are observed in the barnacles indicating the primary reason for blistering is barnacle penetration and diffusion of chlorides and sulfur due to barnacle penetration. In the long term, a buildup of barnacles will act as a barrier to corrosion and reduce cathodic protection current demand.
- No accelerated corrosion was observed inside blisters, only a passivating film on the steel surface. There are many coated pipelines in service with blisters without any evidence of corrosion of the substrate even after 30-40 years.

- The ocean water is very corrosive to bare, unprotected (no coating or cathodic protection) carbon steel, with measured corrosion rates of 6.47 to 8.04 mils per year. However, this corrosion rate was not observed after four years due to barrier effect of the coating, cathodic protection and high pH in blisters.

LABORATORY INVESTIGATION

The laboratory investigation consisted of scanning electron microscopy/energy dispersive x-ray spectrometry (SEM/EDS) of coating samples, Fourier transform infrared spectroscopy (FTIR) of coating samples, ocean water chemical analysis and corrosivity measurements, and cathodic protection data analysis.

Scanning Electron Microscopy/Energy Dispersive X-Ray Spectrometry (SEM/EDS)

A Tescan Vega 3 XMH scanning electron microscope equipped with an EDAX energy dispersive x-ray spectrometer was used to perform the analysis.

Figures 9 and 10 present the EDS data collected from the back side of the coating from adhesion test dollies on Pile 13. The primary elements found in the analysis were carbon (C) and oxygen (O), at 33 weight percent or greater. Secondary elements found in all samples between 1 and 10 weight percent included sodium (Na), aluminum (Al), and silicon (Si). Elements found in amount of 1 weight percent or less include magnesium (Mg), chlorine (Cl), potassium (K), and iron (Fe). This elemental chemistry is consistent with exposure to salt water from the ocean.

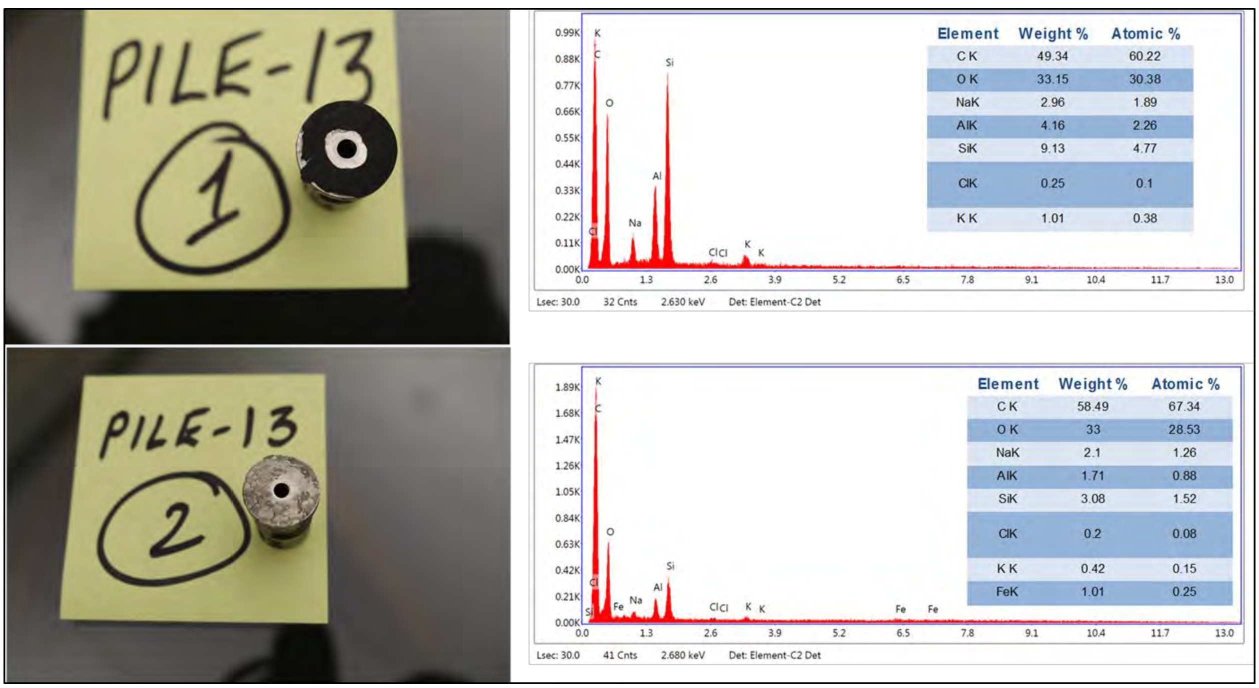

Figure 9: EDS data collected from the back side of the coating of the test dollies 1 and 2.

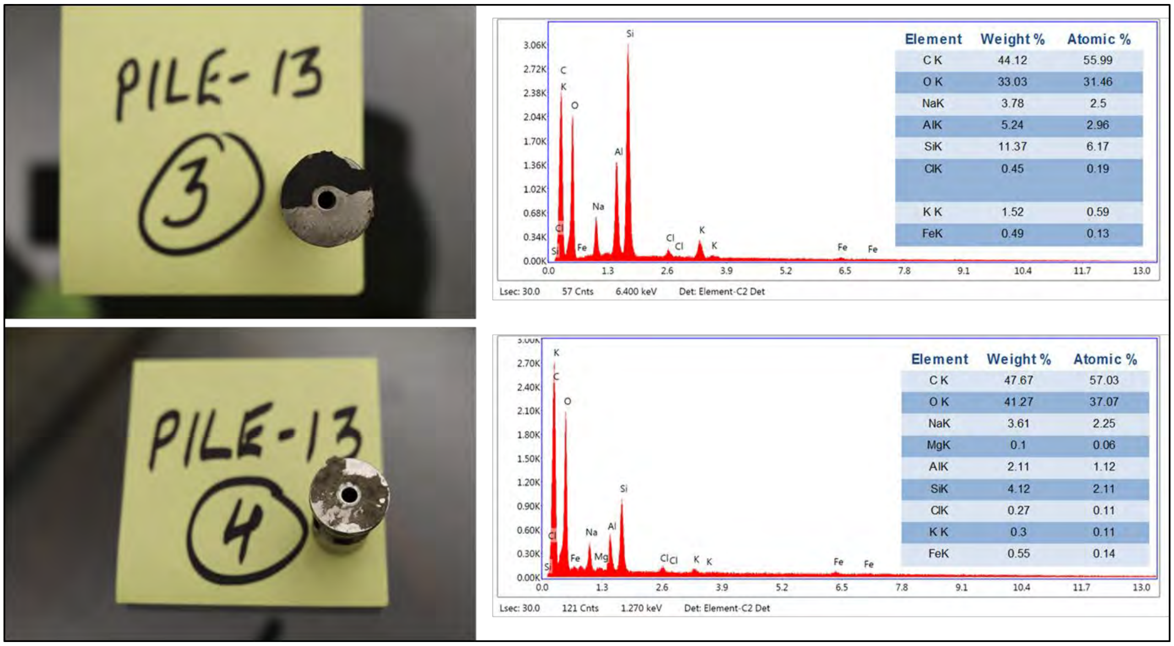

Figure 10: EDS data collected from the back side of the coating of the test dollies 3 and 4.

Figure 11 presents EDS data collected from the front side of the coating sample extracted from plate 77 of Pile 7. Elements identified above one weight percent (in descending order) include oxygen, sodium, silicon, aluminum, chlorine, sulfur (S), calcium (Ca), magnesium, potassium, and phosphorus (P).

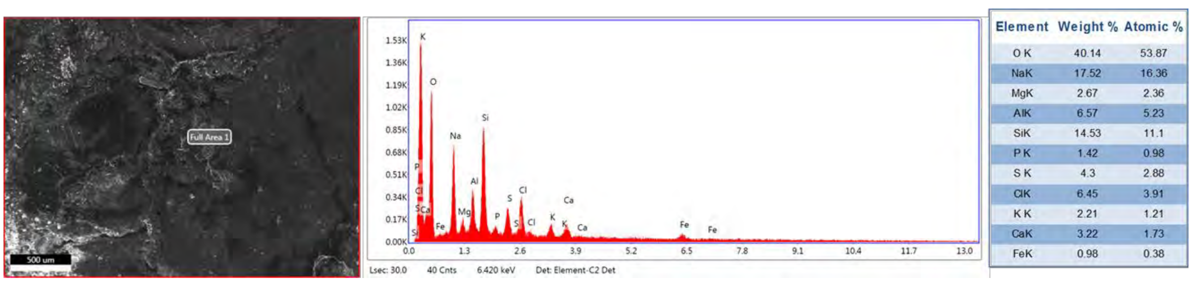

Figure 11: EDS data collected from the front side of the coating sample extracted from plate 77 of Pile 7.

Fourier Transform Infrared Spectroscopic (FTIR) Analysis

The following coating chip samples were subjected to FTIR analysis, using a Nicolet Avatar 360 FTIR spectrometer in attenuated reflectance (ATR) mode.

- "Pile 13 Coating Delamination and Cracking" – both front (facing water), shown in Figure 12. and back (substrate interface) sides.
- "Pile 13 Coating Bulging OD Surface" - both front (facing water) and back (substrate interface) sides.

For all four spectra, a definitive coating chemistry could not be confirmed due to degraded coating resin. As the coating was known to be an epoxy, exposure to the ultraviolet rays found in sunlight are likely responsible in large part for this degradation.

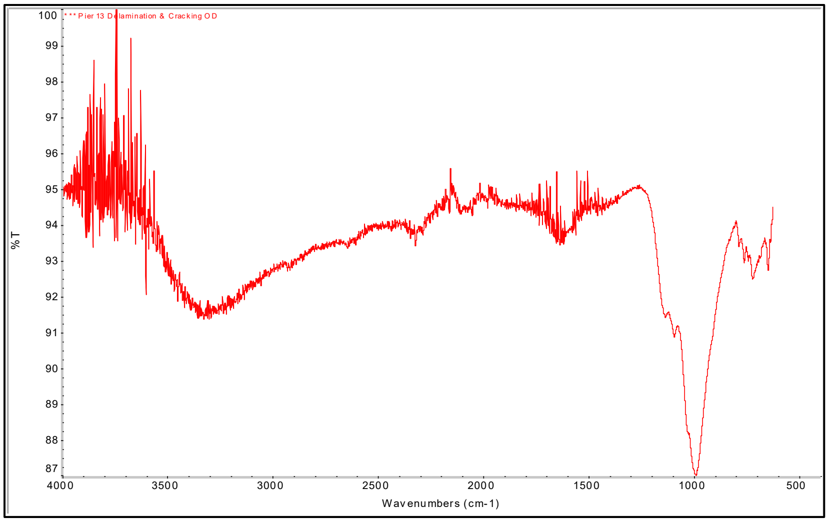

Figure 12: FTIR spectrum of coating chip "Pile 13 Coating Delamination & Cracking" front side (degraded coating resin).

Ocean Water Chemical Analysis and Corrosivity Measurements

Table 1 presents the results of the chemical analysis of five collected samples of ocean water, including conductivity in millisiemens (ms), linear polarization resistance (LPR) corrosion rate of C1010 carbon steel in mils per year (mpy), chlorides in parts per million (ppm), and pH. The data shows the ocean water to range in conductivity from 70.40 to 78.90 ms and the LPR corrosion rate of carbon steel to range from 6.47 to 8.04 mpy. The range of chlorides is 19,600 28,800 ppm, and the pH range is 6.66 to 7.30. In summary, the salty water is very corrosive to bare, unprotected (no coating or cathodic protection) carbon steel.

Table 1
Chemical analysis of five collected samples of ocean water, including conductivity in millisiemens (ms), linear polarization resistance (LPR) corrosion rate of C1010 carbon steel in mils per year (mpy), chlorides in parts per million (ppm), and pH.

	Sample ID	Conductivity ms	LPR mpy	Chlorides ppm	pH
1	5A	78.90	7.27	19,600	6.66
2	13	74.00	7.79	23,800	7.11
3	7/78	70.40	8.04	24,700	7.30
4	11	73.40	7.20	28,700	7.23
5	4A	72.50	6.47	28,800	7.10

Cathodic Protection Data Analysis

The potential data collected during the on-site investigation was plotted to determine the effectiveness of cathodic protection at the site. The AMPP criteria for cathodic protection is a maximum of -850 millivolts or -0.85 volts (v) vs $Cu/CuSO_4$). Figure 14 presents a plot showing potential survey data collected from

Pile 13 to Pile 10 (2nd Bumper). Potential readings here ranged between -1.1 and -1.2 v and reveal that the piles are receiving adequate cathodic protection.

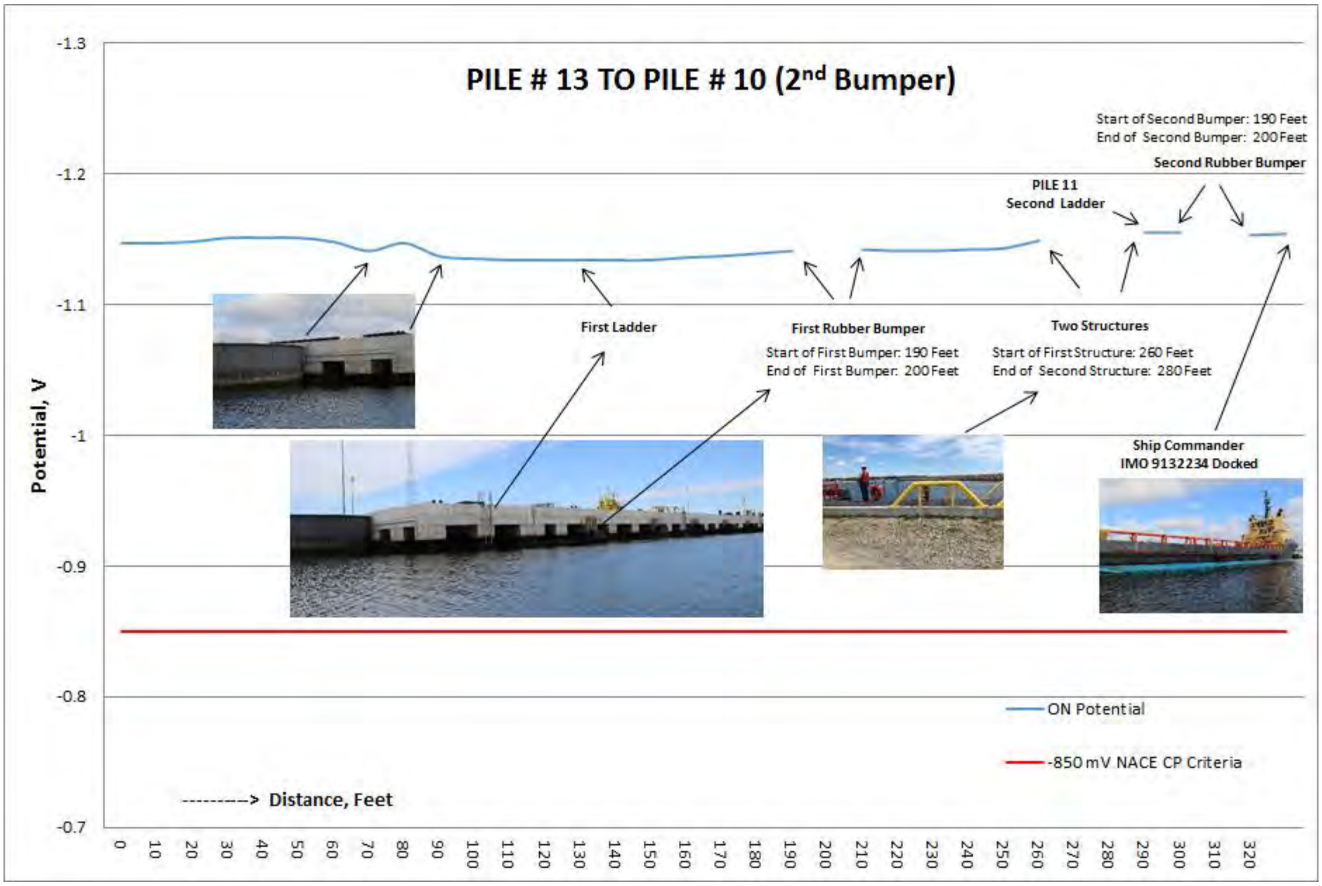

Figure 14: Plot showing potential survey data collected from Pile 13 to Pile 10 (2nd Bumper). Potential readings reveal that the piles are receiving adequate cathodic protection.

Figure 15 presents a plot showing potential survey data collected at Pile 10 (2nd Bumper) from water surface to a depth of 14 feet in the water. Potential readings here range from -1.146 to -1.158 v and reveal that the Pile 11 is receiving adequate cathodic protection. However, the potentials are on the negative side and promote disbondment and further blistering. The potentials should be brought down to more positive numbers than -0.90 v range.

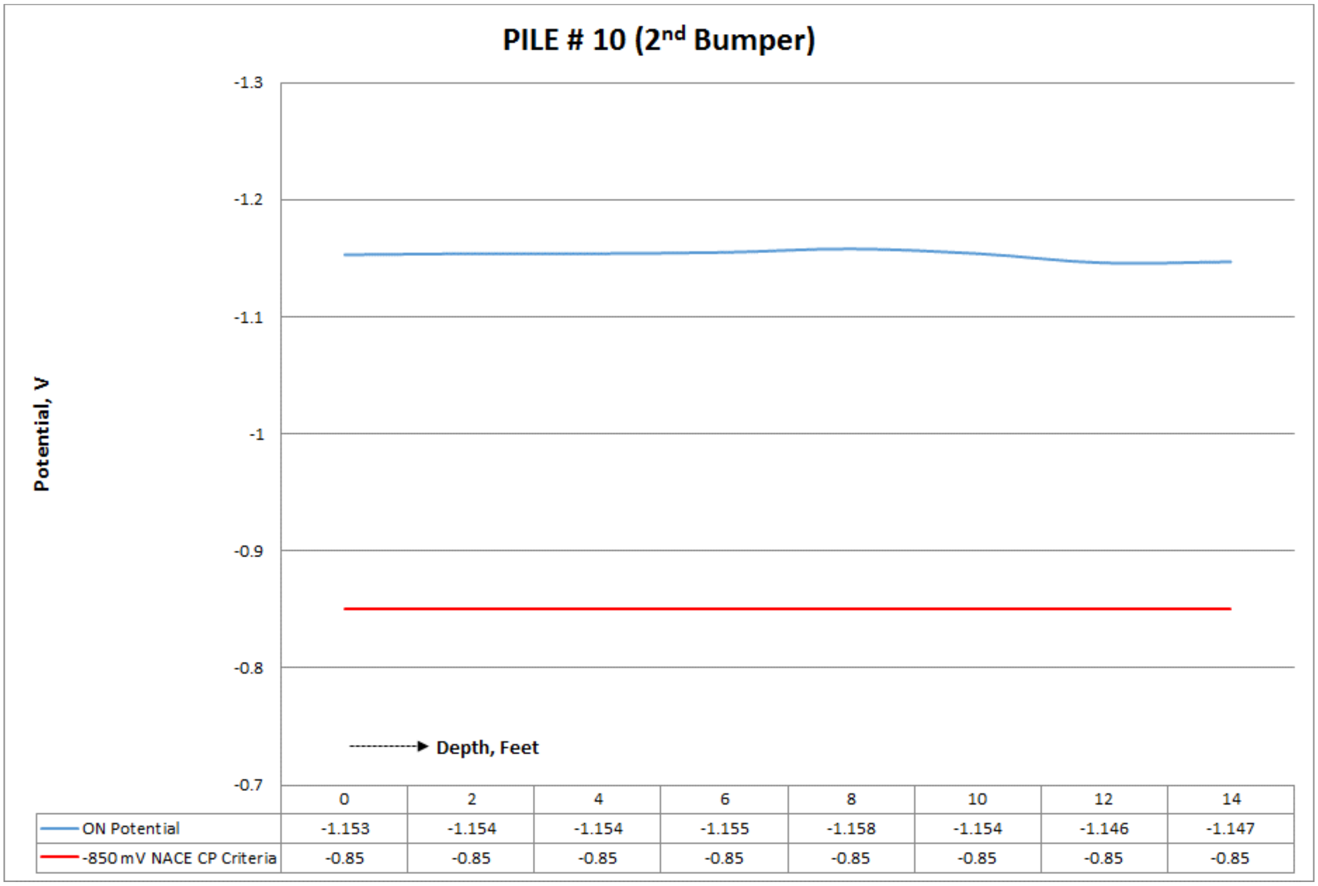

Figure 15: Plot showing potential survey data collected at Pile 10 (2nd Bumper) from water surface to a depth of 14 feet in the water. Potential readings reveal that the pile11 is receiving adequate cathodic protection.

Summary of Laboratory Investigation

The important findings of the laboratory investigation were the following.

- The presence of chlorides and sulfur was confirmed on the back side of coating samples by SEM/EDS analysis which indicates possible prior contamination either during transportation of steel from overseas or exposure to sea environment
- The ocean water is very corrosive to bare, unprotected (no coating or cathodic protection) carbon steel, with measured corrosion rates of 6.47 to 8.04 mils per year. However, due to barrier effect of the coating and the cathodic protection there was no signs of corrosion on the base material.
- Analysis of field collected potential data shows that cathodic protection is adequate if potentials are lowered to more positive values and will provide protection for remaining life.

CONCLUSIONS

Synthesizing the findings of the document review, the on-site investigation, and the laboratory investigation, several conclusions concerning the coating performance on the steel piles at the marine commerce terminal in coastal New England are presented here.

- Specifications supplied and approved for the paint coating system were inadequate for long term service without the utilization of cathodic protection services.
- After four years, the paint coating looks good in non-repaired areas - no corrosion or blisters were observed in non-repaired areas in the atmospheric zone or in areas where there is no mechanical damage or barnacles.
- Maintenance/repair coating of damaged areas to the steel sheets and piles combined with cathodic protection monitoring will ensure that the design life of the steel sheets and piles will be achieved.
- No corrosion or accelerated corrosion in blisters under water was observed due to cathodic protection - the steel surface under the coating blisters is free from corrosion or accelerated corrosion due to high pH and cathodic protection.
- All indications are that barnacles contributed and may have caused the blisters.