Evaluation of the Effectiveness of Salt Neutralizers for Washing Snow and Ice Equipment

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16. Abstract In winter maintenance, the chloride-based deicers used to keep roadways clear of snow and ice are highly corrosive to vehicles and equipment. Corrosion of snow and ice equipment is a major issue causing increased maintenance and repair costs, reduced vehicle life, and increased vehicle downtime. Statistics show that road salt causes approximately $1500/ton of damage to vehicles, bridges, and the environment. Washing of winter maintenance equipment after exposure to ice control chemicals has been suggested as one possible solution to minimize corrosion. However, washing with soap and water has been shown to be insufficient in removing residual salt from winter maintenance vehicles. Treating winter maintenance equipment with salt neutralizers, used in a variety of household and industrial applications, has been shown to prevent corrosion.

Although the consensus points to the need for a reliable and easy to implement corrosion prevention strategy, at present there is not sufficient information available to determine the effectiveness of different wash systems at preventing corrosion. As the corrosion reduction data of salt neutralizer solutions on bare and coated metal surfaces is lacking, a systematic study has been carried out to provide quantitative information. A parallel study of six commercially available salt neutralizers is carried out for comparison. Analysis of the salt neutralizer solutions was carried out using contact angle, Ultra Violet-visible spectroscopy (UV-vis), and Scanning Electron Microscopy imaging (SEM). Corrosion inhibition for several metals treated with salt neutralizer was determined using potentiodynamic measurements and accelerated weight loss analysis (ASTM B117). When considering the effects of corrosion on winter maintenance equipment, it is important to study not only steel but also various "soft metals" (copper, aluminum, brass, etc.) that can be found in the wiring and other parts of the fleet. Electrical Impedance Spectroscopy and visual inspection were used to determine the ability of coated metal samples to prevent corrosion. A cost benefit analysis was completed to determine what specific conditions directly impact the cost effectiveness of corrosion prevention strategies.

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LIST OF ACRONYMS

ASTM - American Society for Testing and Materials

CMC- Critical Micelle Concentration

CDOT- Colorado Department of Transpiration

EAUC- Equivalent Uniform Annual Costs

EDX- Energy Dispersive X-ray

FHWA – Federal Highway Administration

HSM – Highway Safety Manuel

IHRB - Iowa Highway Research Board

NCHPR – National Cooperative Highway Research Program

NACE- National Association of Corrosion Engineers

NCWE- Neutralizer Cost per Truck per Wash Event

NCWS- Neutralizer Cost per Facility per Winter Season

ODOT- Ohio Department of Transportation

OEM- Original Equipment Manufacturer

RWIS – Road Weather Information System

SAE- Society of Automotive Engineers

SCC- Stress Corrosion Cracking

SEM-Scanning Electron Microscope

TMS – Transportation Management Services

TRB – Transportation Research Board

UV-vis- Ultraviolet-visible

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EXECUTIVE SUMMARY

In winter maintenance, the chemicals used to keep roadways clear of snow and ice are highly corrosive to vehicles and equipment and causes increased maintenance and repair costs, reduced vehicle life, and increased vehicle downtime. Coatings are often used applied to protect the bare from corrosive environments. However, even with a protective coating, once a sufficient amount of chloride ions (from salt) pass through the coating to the underlying metal, a more aggressive corrosion environment is formed forcing the coating blister and peel-off. This is further accelerated when there are breaches or holidays on the surface of the coating.

Washing of winter maintenance equipment after exposure to ice control chemicals has been suggested as one possible solution to minimize corrosion in winter maintenance equipment. Washing with soap and water, however, has been shown to be insufficient in removing residual salt from winter maintenance vehicles. Salt neutralizers have been suggested as one possible solution to clean the difficult to remove salt residue but there is insufficient information available to determine the cost-benefit of different wash systems and salt neutralizing products.

As part of this research, the current state of corrosion prevention strategies was assessed through a literature review and interviews with ODOT districts. Interviews were conducted with ODOT personnel to identify a range of corrosion prevention strategies. Based on feedback from these interviews, a total of six salt neutralizers and three coatings were deemed appropriate for consideration by ODOT. A detailed investigation of the effectiveness of each of the corrosion prevention strategies was conducted. This included laboratory-scale accelerated corrosion testing on bare and coated metal samples and an analysis of the cost of each strategy.

Laboratory-scale testing was performed in the Monty Research Laboratory at the University of Akron and at Light Curable Coatings in Berea, OH. Due to the time-scale of the proposed project, accelerated corrosion testing procedures were necessary in order to investigate the effectiveness of salt neutralizers on the laboratory scale. Metal coupons fall into three categories: bare, coated (unscribed), and coated (scribed). Coatings were scribed following ASTM D1654-08 procedures. All testing methods were modified to include a salt neutralization step on the metal coupons tested. A reference set of coupons will be tested using the standard test method.

A comprehensive literature review and comprehensive email survey of ODOT districts was conducted to identify current practices for corrosion prevention on snow and ice equipment. Email survey results showed that 37% of respondents use a salt neutralizer to prevent corrosion due to exposure to deicing solutions. Of these respondents, the large majority use Neutro-wash™ as the selected salt neutralizer; while two respondents use ConSALT. Additionally, 80% listed cost as the main reason for discontinued use of salt neutralizer solutions in corrosion prevention.

Modified SAE J2234 accelerated corrosion testing was performed with the two aluminum alloys and three salt neutralizers and A36 with six salt neutralizers. These tests were compared to soap and water and water washing alone to determine the ability of the salt neutralizer to prevent corrosion. SAE J2234 testing shows that the aluminum alloys are not corrosive enough to monitor corrosion rate after 6 weeks of testing. Testing on A36 also showed that the corrosion rate was not large enough to compare wash procedures.

Accelerated corrosion testing (modified ASTM B11 was performed with seven metal alloys (2024 aluminum, 5086 aluminum, 304 stainless steel, 410 stainless steel, A36 carbon steel, copper, and brass) and six salt neutralizers. These tests were compared to soap and water and water washing alone to determine the ability of the salt neutralizer to prevent corrosion. Test results show that the ability of salt neutralizers to prevent corrosion is alloy specific. For example, use of some salt neutralizers accelerated corrosion on steel alloys but showed some corrosion prevention on aluminum alloys. Salt-away™ was the top-performing salt neutralizer as it reduced corrosion on all metal samples. Neutro-wash™ was also effective at preventing corrosion on copper and aluminum. Pure vinegar and 5 weight percent sulfamic acid showed reduced corrosion on carbon steel and were used as a control.

Testing also indicated that salt neutralizer performance was greatly affected by dilution rate. After increasing the volume percentage of salt neutralizer in the wash solution, all salt neutralizers prevented corrosion on carbon steel. However, increasing volume percentage of salt neutralizer in the wash solution will decrease cost effectiveness of the neutralizer.

After completion of accelerated corrosion testing on bare metal samples, testing was carried out on coated metal samples using the three overall, top-performing salt neutralizers from bare metal testing. Accelerated corrosion testing was performed on five metal alloys (2024 aluminum, 5086 aluminum, 304 stainless steel, 410 stainless steel, A36 carbon steel) and three coatings (original equipment manufacturer (OEM), UV-Curable coating, and LubraSeal™). These tests were compared to soap and water and water washing alone to determine the ability of the salt neutralizer and coating to prevent corrosion. Again, testing results show that the ability of coatings and salt neutralizers to prevent corrosion is alloy specific. For example, coated aluminum alloys did not exhibit corrosion while coated carbon steel samples were highly corroded.

Based on accelerated corrosion testing, the UV-curable coating is the most effective at preventing corrosion on metal samples; while, OEM coatings and LubraSeal™ both show visible coating deterioration and rusting. Statistically, neutralizer application did not inhibit corrosion on the majority of carbon steel scribed samples. However, the average creep rates for Salt-away and Eastwood were better than soap and water on LCC coated metal coupons. These results were corroborated with EIS testing that indicates that Salt-away and Eastwood increase corrosion protection on carbon steel samples coated with LCC.

EIS tested was also used to validate visual inspection. Testing indicated that although some coatings did not appear corroded or blistered during visual inspection, there was indeed a breakdown in corrosion protection occurring at the metal surface. For example, OEM painted samples showed a decrease in coating performance after salt spray testing, even with neutralizer application. LCC coatings, however, maintained coating performance.

Cost analysis showed that specific conditions directly impact the cost and effectiveness of corrosion prevention strategies. The metal alloy of interest, dilution of the salt neutralizer wash, and the type of coating are necessary for determining an ideal prevention strategy at individual garages. The cost to thoroughly wash a single truck is significant and can vary by more than 300% depending on the neutralizer product. For the two top performing (at “modified” dose to achieve corrosion reduction) neutralizer products (Salt-Away and BioKleen) and Neutro-Wash, the neutralizer cost for a full 350 gallon wash per truck would be $567 for Salt-Away, $1,043 for BioKleen, and $1,810 for Neutro-Wash.

Assuming replacement cost of ODOT tandem truck is ~$140,000 ($125,000 single axle) and the neutralizer solution can increase the useful life of the truck by 6 months to 1 year, washing the trucks with Salt-Away 5 to 18 times per year (depending on facility location and replacement cycle) is cost-effective. The benefits could be even greater if the maintenance costs associated with wiring etc. are also reduced.

CHAPTER I

INTRODUCTION

1.1. Problem Statement

In winter maintenance, chloride-based deicers can be extremely corrosive to snow and ice equipment. When considering the effects of corrosion, it is important to consider not only steel but also various "soft metals" such as copper, aluminum, chrome, and brass that can be found in the wiring and other parts of the equipment. Washing of winter maintenance equipment after exposure to ice control chemicals has been suggested as one possible solution to minimize corrosion in winter maintenance equipment. Washing with soap and water, however, has been shown to be insufficient in removing residual salt from winter maintenance vehicles. Salt neutralizers have been suggested as one possible solution to clean the difficult to remove salt residue. There is consensus about the need to develop reliable and easy to use wash procedures to prevent corrosion. At present, however, there is not sufficient information available to determine cost versus benefit of different wash systems with or without the use of salt neutralizers. A thorough evaluation of the effectiveness of the salt neutralizers to reduce the corrosion rate on bare and coated metal surfaces would facilitate the future effective use of neutralizing products.

Commercially available salt neutralizer solutions contain an acid component to remove corrosive chloride residue from the surface of the metal. However, the acid itself can be highly corrosive and could potentially increase corrosion. Corrosion inhibitors, typically surfactants, are also added to salt neutralizer to solutions to protect the metal surface during the washing process. Surfactants inhibit corrosion by forming a protective barrier at the surface of the metal. Therefore, corrosion inhibition by a surfactant is directly related to the ability of the surfactant to aggregate at the metal surface, the surfactant type and concentration. This makes the overall neutralizer effectiveness complicated and generally unknown for different metal surfaces and truck washing conditions. Finally, the combination of protective coatings and salt neutralizer application to metal surfaces has not been evaluated.

1.2. Objectives and Goals of the Study

The four objectives of this project were as follows:

- Objective 1 - Perform a thorough literature search on the effectiveness of salt neutralizers as reported by other state DOTs,
- Objective 2 - Assess selected, commercially-available salt neutralizer products in removing salt residue and preventing corrosion in the laboratory on various bare and coated metal surfaces,
- Objective 3 - Perform a cost-benefit analysis of the top-performing salt neutralizing product, and
- Objective 4 - Propose a deployment strategy for the salt neutralizing product consistent with current ODOT practices.

1.3. Overview of Approach

To meet the four objectives identified above and to provide a cost effective corrosion prevention strategy for winter maintenance equipment, this research team developed and completed four research tasks.

Task One: Evaluation of Available Data and Reports on the Effectiveness of Salt Neutralizers and Coatings

The main goal of this task was to evaluate and summarize available data and reports from ODOT districts that are currently using salt neutralizer washes to remove salt residue on their winter maintenance vehicles. The majority of the questions focused on:

- General maintenance questions involving incorporating salt neutralizers into wash protocol on both bare metal and coated surfaces,

- The preferred commercially available salt neutralizer and the preferred application rate/method,
- The preferred commercially available coatings and the preferred application rate/method
- General in-field performance of the salt neutralizer on bare metal and coated surfaces,
- Features within the salt neutralizer and coating products that are liked and disliked, and
- Feedback including the effectiveness at the salt neutralizers at reducing corrosion on coated and uncoated surfaces.

The information provided by individual garages on corrosion prevention strategies and costs aided in the identification of viable salt neutralizers and corrosion protective coatings for use in laboratory experiments.

Task Two: Data Collection

Table 1-1: Testing conditions used for accelerated corrosion testing in the ASTM B117 salt spray chamber

	Bare Metal	**Coated Metal (scribed)**	**Coated Metal (unscribed)**
Metals Tested	Aluminum 2024 Aluminum 304 Stainless Steel 4 Stainless Steel Carbon Steel (A36) Copper Brass	Aluminum 2024 Aluminum 304 Stainless Steel 4 Stainless Steel Carbon Steel (A36)	Aluminum 2024 Aluminum 304 Stainless Steel 4 Stainless Steel Carbon Steel (A36)
Commercial Neutralizers and Soap and Water	BioKleen ConSALT Eastwood Neutro-wash Salt-away WinterRinse Soap and Water Water Vinegar Sulfamic acid	Eastwood Neutro-Wash Salt-away Soap and Water Water	Eastwood Neutro-Wash Salt-away Soap and Water Water

Using the information collected under Task One, options were identified and evaluated as potential corrosion prevention strategies that contained both salt neutralizer washes and corrosion protective coatings. The feasibility of these options was evaluated based on results of laboratory experiments and accelerated corrosion testing (ASTM B117, SAE J2334). Table 1-1 shows the testing conditions used in this Task. Laboratory-scale testing was performed in the Monty Research Laboratory at the University of Akron and at Light Curable Coatings in Berea, OH.

Task Three: Benefit to Cost Analysis Using Commercially Available Salt Neutralizers

Using the information obtained in Tasks One and Two, a benefit-cost analysis was be performed in order to compare the effect of salt neutralizers on overall cost taking equipment maintenance and usable lifetime into consideration. For this comparison, the principal measures are total capital cost (incorporating initial maintenance equipment costs, replacement costs, and salt neutralizer application costs) and routine and emergency maintenance costs.

Task Four: Recommended Washing Strategy Using Salt Neutralizers With and Without Protective Coatings

The last task was to make a final recommendation for implementation of the research including effective washing procedures (e.g. effective dilutions) and corrosion prevention strategies.

1.4. Report Organization

This report is organized into six chapters. Chapter 1 summarizes the goals and objectives of this project as well as the general approach to meeting these objectives. Chapter 2 provides background information including a review of relevant literature and current strategies for corrosion prevention in Ohio and across the country. Chapter 3 summarizes and analyzes the results of the accelerated corrosion testing on bare metal samples, and Chapter 4 summarizes and analyzes the results of the accelerated corrosion testing on coated metal samples. Chapter 5 discusses the costs and benefits of corrosion prevention strategies including salt neutralizers and corrosion protective coatings. Chapter 6 summarizes the results of this research and provides recommendations for implementation.

CHAPTER II

BACKGROUND

2.1. Introduction

Current estimates suggest that the United States loses over $220 billion dollars due to corrosion each year while 15% of that loss is avoidable (Xiong 2009). In winter maintenance, the chemicals used to keep roadways clear of snow and ice are highly corrosive to vehicles and equipment (Chance 1974). Corrosion of snow and ice equipment is a major issue causing increased maintenance and repair costs, reduced vehicle life, and increased vehicle downtime. Statistics show that road salt causes approximately $1500/ton of damage to vehicles, bridges, and the environment (Xiong 2009). Coatings are often used applied to protect the bare from corrosive environments. However, even with a protective coating, once a sufficient amount of chloride ions (from salt) pass through the coating to the underlying metal, a more aggressive corrosion environment is formed forcing the coating blister and peel-off. This is further accelerated when there are breaches or holidays on the surface of the coating.

Washing of winter maintenance equipment after exposure to ice control chemicals has been suggested as one possible solution to minimize corrosion in winter maintenance equipment. Washing with soap and water, however, has been shown to be insufficient in removing residual salt from winter maintenance vehicles. Salt neutralizers have been suggested as one possible solution to clean the difficult to remove salt residue but there is insufficient information available to determine the cost-benefit of different wash systems and salt neutralizing products (Xiong 2009).

2.2. Corrosion of Snow and Ice Equipment

In winter maintenance, the chloride-based deicers can be extremely corrosive to snow and ice equipment. When considering the effects of corrosion, we must consider not only steel but also various “soft metals” (copper, aluminum, chrome, brass, etc.) that can be found in the wiring and other parts of the fleet. The corrosion of winter maintenance equipment has become more of an issue as the use of liquid deicers is increasing (Xi and Xie 2002; Baroga 2004; Xiong 2009).

The basic mechanisms of corrosion are well studied and understood. These include uniform corrosion, inter-granular corrosion, galvanic corrosion, crevice corrosion, pitting corrosion, erosion corrosion, stress corrosion cracking, biological corrosion, and selective leaching. Based on electrochemical theory, a complete corrosion reaction is divided into both anodic and cathodic reactions that occur simultaneously at discrete points on metal surfaces. Electrons are transferred between the anode and cathode found on either single metallic surfaces or dissimilar metals. When liquid is present, electrons are captured in solution and the metal gradually becomes ionic and dissolves into solution. Figure 2-1 illustrates the basic galvanic cell associated with the corrosion of iron. When a water droplet is present on the surface, the cathode reduces oxygen from air forming hydroxide ions while the anode causes the dissolution of iron. Chloride ions found in deicing solutions do not chemically react with the metal surface. However, chloride ions accelerate the corrosion rate by acting as a medium or catalyst for the electrochemical reaction(Uhlig and Revie 1985; Fitzgerald 2000).

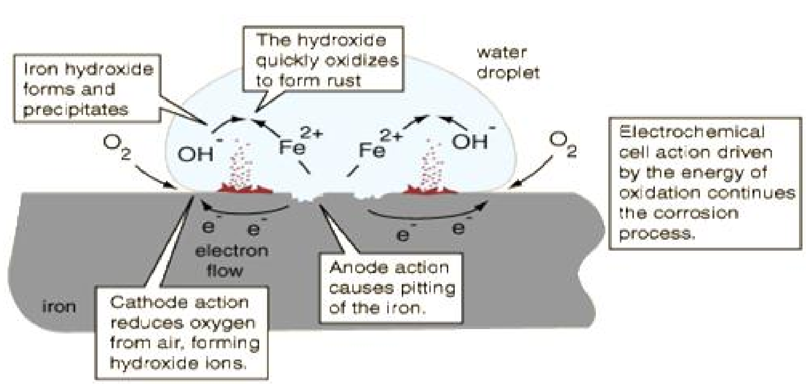


Figure 2-1: Basic Mechanism for Iron Corrosion (figure taken from http://hyperphysics.phy-astr.gsu.edu/hbase/chemical/corrosion.html)

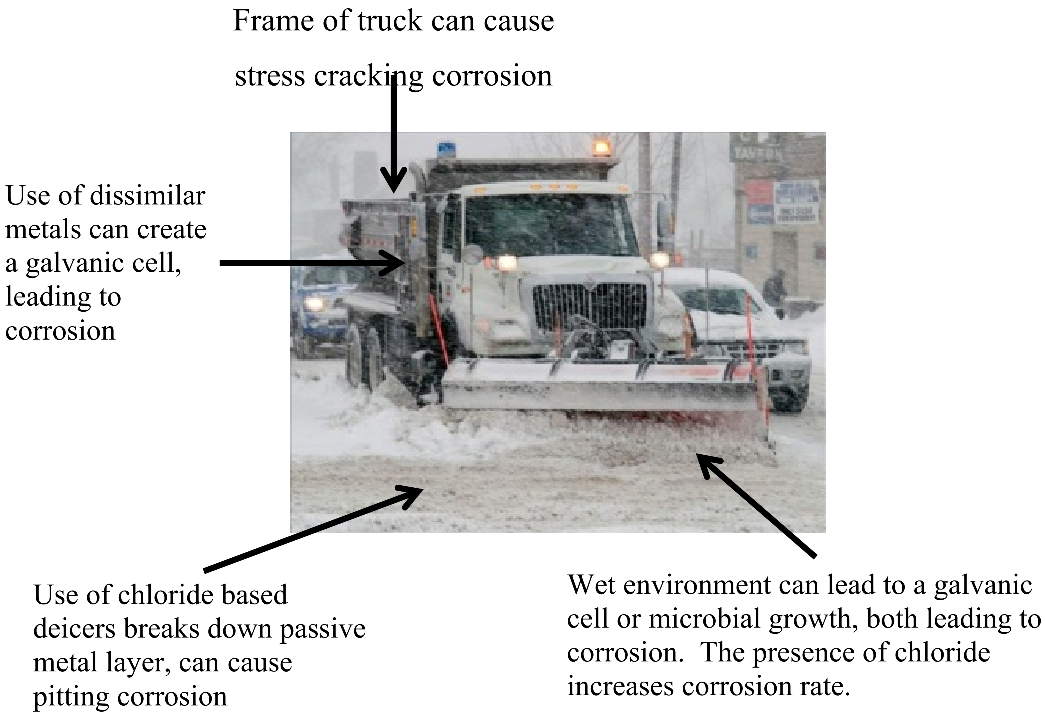


Figure 2-2: Overview of Corrosion on Snow and Ice Equipment

Figure 2-2 illustrates some of the main causes of corrosion for snow and ice equipment. Not all possible corrosion mechanisms are responsible for the deterioration of such equipment, but several are highly prevalent. Specific factors causing corrosion of snow and ice equipment are (1) the use of chloride based deicers breaks down the protective layer causing pitting corrosion, (2) the wet environment which allows for the easier creation of a galvanic cell, (3) high corrosion current of liquids, (4) penetration of liquids into areas not accessible by solids, (5) liquids may cause differential aeration, (6) presence of micro-organisms giving rise to biological corrosion, (7) presence of dissimilar metals found in many truck locations that can give rise to a galvanic cell, and (8) frame of the truck creating a load allowing for stress corrosion cracking (Xi and Xie 2002; Baroga 2004; Xiong 2009).

Several reports have been published to discuss the specifics of corrosion on winter maintenance equipment. The first study was conducted for the Colorado Department of Transportation (CDOT) and considered the effect of magnesium chloride versus sodium chloride on vehicular corrosion. This report found that there was significant corrosion on metal coupons placed on 10 different winter maintenance vehicles (Figure 2-3). Researchers found that corrosion was prevalent in both salt solutions and varied depending on conditions. This study, however, did not correlate corrosion to salt exposure or winter weather conditions and could therefore not correlate the effectiveness of laboratory experiments for the prediction of corrosion(Xi and Xie 2002).

Figure 2-3: Metal coupons used to measure corrosion on winter maintenance vehicles. Corrosion rate was measured as weight lost over time due to exposure of the coupons to two different salt solutions (Xi and Xie 2002).

The second report was published by the Washington DOT Salt Pilot Project where a field-test was conducted along I-90 in Eastern Washington. In this work, steel and aluminum coupons were used to evaluate the effect of corrosion-inhibitors on vehicular corrosion. The researchers found that the corrosion-inhibited chemicals provided some level of corrosion reduction; however, the corrosion rates were not comparable to the results gathered from standard laboratory analysis. These two studies show the importance of testing corrosion reduction strategies in the field and also highlight the need for a predictive model to determine corrosion rate due to different environmental conditions (Baroga 2004).

Most recently, the Iowa Highway Research Board (IHRB) investigated materials for the reduction and prevention of corrosion on highway maintenance equipment. This study presented several conceptual solutions to mitigating corrosion in the field including 1) the use of inhibitors in ice control chemicals, 2) use of washing systems, 3) design changes, and 4) use of coatings. Investigators also determined that seven of eight responses to a survey on corrosion mitigation listed washing of vehicles as the primary role of corrosion prevention practices. One noted, “Anodes, protective coatings, etc. haven’t done nearly as much for our fleet as a good old fashioned shot of hot water with soap." Another responder noted that "post storm washing and lubrication in the foundation to effect preventative maintenance." Several other responders noted using salt neutralizing products such as Neutro-wash to remove the chloride residue as frequently as after each event (Xiong 2009).

2.3. Corrosion Protective Coatings

One way to prevent corrosion is through the use of corrosion protective coatings. These coatings have been shown to protect bare metal components from corrosion-causing conditions such as moisture, salt spray, oxidation, etc. Figure 2-4A shows the effect a UV-cured coating developed at Light Curable Coatings on the corrosion of a 2024 aluminum alloy. Notice that after 3000 hours in a salt spray chamber, the coating had protected the aluminum from undergoing any visible corrosion.

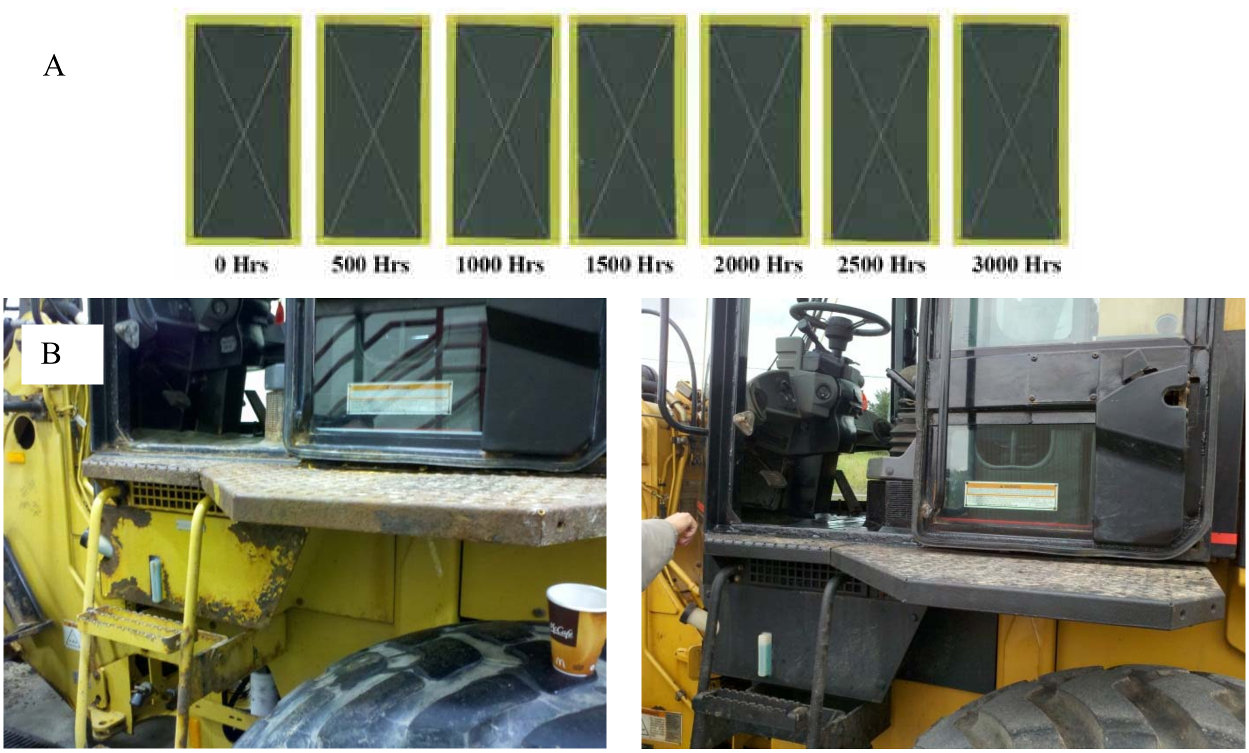


Figure 2-4A: Effect of UV-curable coating on corrosion of an aluminum alloy after exposure to 3000 hours of salt spray testing. B. In-field success of corrosion protective coating applied to winter maintenance equipment.

Figure 2-4B shows the effect of in-field implementation of corrosion protective coatings on protecting winter maintenance equipment from undergoing corrosion. The picture on the left is without a protective coating and the picture on the right is after application of a coating. Notice that there is less corrosion on the surface of the winter maintenance equipment with the protective coating. Even with a protective coating, however, once a sufficient amount of chloride ions (from salt) pass through the coating to the underlying metal, a more aggressive corrosion environment is formed that causes the coating blister and peel-off. This is further accelerated when there are breaches or holidays on the surface of the coating. Therefore, long-term exposure of winter maintenance equipment to strong deicers will lead to corrosion even when the equipment is protected with corrosion protective coatings. Although the consensus points to the need for a reliable and easy to use wash system to prevent corrosion, at present there is not sufficient information available to determine the cost-benefit ratio for different wash systems with or without the use of salt neutralizers with and without protective coatings.

2.4. Commercially Available Salt Neutralizing Products

Currently there are several commercially available salt neutralizing products. Salt neutralizers act by solubilizing hard scales that can cause corrosion of a metal surface and are typically composed of either sulfamic or hydrochloric acid. Sulfamic acid is the monoamide of sulfuric acid and acts as a strong acid in aqueous solution; however, the corrosivity of sulfamic acid is considerably lower than other strong acids (Malik, 2011). Another key advantage of sulfamic acid is that it can be used to clean metal surfaces without causing chloride induced stress corrosion cracking (SCC).

Addition of a corrosion inhibitor to a strong acid cleaning solution is essential in protecting the surface of the metal during the cleaning process. For salt neutralizer solutions, surfactants are typically used as corrosion inhibitors. Adsorption of surfactant molecules onto a metal surface has been shown to inhibit corrosion by forming a barrier film. The degree of adsorption depends on the surface of the metal and the surface condition, the mode of adsorption, the structure of the surfactant itself, and the corrosion media. The advantages of surfactant-based corrosion inhibitors are “high inhibition efficiency, low price, low toxicity, and easy production” (Malik, 2011). Table 2-1 below contains information on the application method and composition for several common salt neutralizers that are currently commercially available.

Table 2-1: Commercially available salt neutralizers and their recommended washing concentrations

Salt Neutralizer	Strong Acid Cleaner	Recommended Washing Concentration (vol. %)
BioKleen	Proprietary	3
ConSALT	Hydrochloric Acid	10
Eastwood	Sulfamic Acid	5
Neutro-wash	Sulfamic Acid	11
Salt Away	Sulfamic Acid	10
Winter Rinse	Sulfamic Acid	4

2.5. Current Corrosion Prevention Strategies in Ohio

As the main focus of this research was the evaluation of corrosion prevention strategies, an online survey was developed using SurveyMonkey (surveymonkey.com) and distributed to all ODOT district managers. The majority of the questions focused on:

- General maintenance questions involving incorporating salt neutralizers into wash protocol on both bare metal and coated surfaces,
- The preferred commercially available salt neutralizer and the preferred application rate/method,
- The preferred commercially available coatings,
- General in-field performance of the salt neutralizer on bare metal and coated surfaces,
- Features within the salt neutralizer and coating products that you like and dislike, and
- Feedback including the effectiveness at the salt neutralizers at reducing corrosion on coated and uncoated surfaces.

All of the survey responses were received from municipalities. The online survey received a total of 51 responses. Raw data responses from this survey can be found in APPENDIX A. The majority of respondents to the online survey indicated that they use sodium chloride (salt) brine in their deicing protocol. The results of type of deicer used by the respondents are listed in Table 2-2.

Table 2-2: Deicing Chemicals and Materials Used

	Response Percent	**Response Count**
Sodium Chloride (Salt) Brine	98.0%	50
Calcium Magnesium Acetate	2.0%	1
Magnesium Chloride	2.0%	1
Calcium Chloride Liquid	88.2%	45
Calcium Chloride Flakes	5.9%	3
Potassium Acetate	0.0%	0
Sand-Grit	45.1%	23
Carbohydrate or Agricultural Based Solutions (i.e.; Beat Heat)	17.6%	9
Other (please specify)		3
answered question		**51**
skipped question		**2**

Of the 51 responses, 37.7% (20 respondents) use a salt neutralizer in their wash protocol. Of those 20 respondents, the majority use Neutro-Wash by Rhomar; with 55% applying the salt neutralizer by hand washing and 65% using a pressure washing system. Two additional respondents listed ConSALT as their salt neutralizer of choice. The average effectiveness, as evaluated by the respondents, of the salt neutralizer is listed in Table 2-3. Overall, respondents found salt neutralizers to be effective in preventing corrosion on winter maintenance equipment. Effectiveness was evaluated by monitoring appearance (visual inspection), experience, and the number of electrical breakdowns of winter maintenance equipment. When asked what features they liked/disliked about the salt neutralizers most respondents answered that it was too soon for them to judge the performance of the salt neutralizer. Respondents who have previously used the salt neutralizer liked the fact that it reduced rust on their equipment.

Table 2-3: Rating of effectiveness of salt neutralizers

Answer Options	**Very effective**	**Effective**	**Slightly effective**	**Not Sure**	**Response Count**
	1	10	3	6	20

Of the 62.3% (31 respondents) of respondents that do not use a salt neutralizer in their wash protocol, 23.5% (8 respondents) have previously used a salt neutralizing product. From those respondents, four listed cost, one respondent listed the ineffectiveness of the salt neutralizer, and two respondents listed time constraints as the reason for the discontinued use of the salt neutralizer. Other responses included lack of use and acid content. The breakdown of the responses is highlighted in Table 2-4.

Table 2-4: Reasons for discontinued use of salt neutralizer

Answer Options	**Response Percent**	**Response Count**
Cost	80.0%	4
Ineffective	20.0%	1
Time constraints	40.0%	2
Other (please specify)		3
	answered question	**5**
	skipped question	**48**

Of the 51 responses, 36.5% (19 respondents) use a corrosion protective coating on their winter maintenance equipment. Of those 19 respondents, the most popular was LubraSeal (by Rhomar). However, some respondents also use Krown T40.

Table 2-5: Rating of effectiveness of coating at preventing corrosion

Answer Options	**Very effective**	**Effective**	**Slightly effective**	**Not Sure**	**Response Count**
	2	9	6	3	20

The average effectiveness, as evaluated by the respondents, of the coatings is listed in Table 2-5. Overall, respondents found coatings to be effective in preventing corrosion on winter maintenance equipment. Effectiveness was evaluated by monitoring appearance (visual inspection), experience, and the number of electrical breakdowns of winter maintenance equipment. When asked what features they liked/disliked about the coatings most respondents answered that it was too soon for them to judge performance. However, respondents who have previously used the coatings listed that it reduced the number of repairs caused by corrosion.

Of the 21 respondents that use a salt neutralizer, 47.6% use a salt neutralizer in combination with a corrosion protective coating. Overall, respondents found the combination of salt neutralizers and coatings to be effective in preventing corrosion on winter maintenance equipment; however, the sample set found that it was still too early to determine effectiveness in the field.

2.6. Overview of Literature and Survey Results

- Literature results on corrosion rates for bare metal surfaces using commercial neutralizer solutions to reduce corrosion on winter maintenance equipment are limited.
- A comprehensive email survey of ODOT districts was conducted to identify current practices for corrosion prevention on snow and ice equipment. Email survey results showed that 37% of respondents use a salt neutralizer. Of these respondents, the large majority use Neutro-wash™ as the selected salt neutralizer. Two other districts use ConSALT

CHAPTER III

EVALUATION OF SALT NEUTRALIZER SOLUTIONS AT PREVENING CORROSION ON BARE METAL SAMPLES

3.1. Introduction

To evaluate the effectiveness of the salt neutralizers determined in Chapter 2, accelerated corrosion testing was performed to compare effectiveness of washing methods compared to water and soap. Initially, this evaluation focused on two metals of interest: stainless steel and aluminum. Accelerated corrosion testing was performed with the help of Ben Curatolo, Ph.D. at Light Curable Coatings in Berea, OH. Results indicate that corrosion prevention is alloy specific and heavily dependent on salt neutralizer concentration. Based on these results, the sampling effort was expanded to include testing of copper, brass, and carbon steel and metal testing at increased salt neutralizer concentration.

3.2. Accelerated Corrosion Testing on Bare Metal Samples

3.2.1. Experimental Procedure used for ASTM B117 Testing

Effectiveness of the salt neutralizer to prevent corrosion on bare metal samples was evaluated using a modified ASTM B117 accelerated corrosion testing procedure (Figure 3-1). In order to provide statistically significant data using ASTM B-117 testing, samples were tested in triplicate. The metals were prepared with a class B polish preparation and the volatile corrosion inhibitor was removed using a DI water, ethanol, acetone, DI water wash. Initially, the dimensions, resistivity, and weight of each metal sample was measured and recorded. Bare metal samples (coupons) were placed in a salt spray chamber (Singleton Corporation, Cleveland, OH, USA) for 48 hours following the specifications from standard ASTM-B117. The pressure of the humidifying tower is kept between 12 and 18 psi, and its temperature between 114 and 121°F, while the chamber is maintained between 92 and 97°F using a salt solution of 5 wt.% NaCl prepared in DI water.

The coupons were treated with the salt neutralizers at 6, 24 and 30 hours after initial setup. The final step involves rinsing with DI water and let the samples air-dry before wrapping them in laboratory cleaning tissues.

Effectiveness of the salt neutralizer to prevent corrosion on the bare metal samples was evaluated using weight loss analysis. After exposure to the salt spray for 48 hours, the metals were prepared for weight loss analysis using the ASTM G1-03 standard to remove the corrosion products formed during experimentation. For aluminum and stainless steel a nitric acid wash was used, for brass and copper a hydrochloric acid wash was used, and for carbon steel the Clark solution was used. After removal of the corrosion products from the metal surface, the samples were weighed and mass loss was determined. Then, the corrosion rate was calculated using the following formula:

$$Corrosion\ Rate\ (CR) = \frac{K \times W}{A \times T \times D}$$

Where K is a constant for unit conversion (3.45x 10^6 mpy), W is the mass loss in grams, A is the area in cm^2, T is the exposure time in hours, and D is the density.

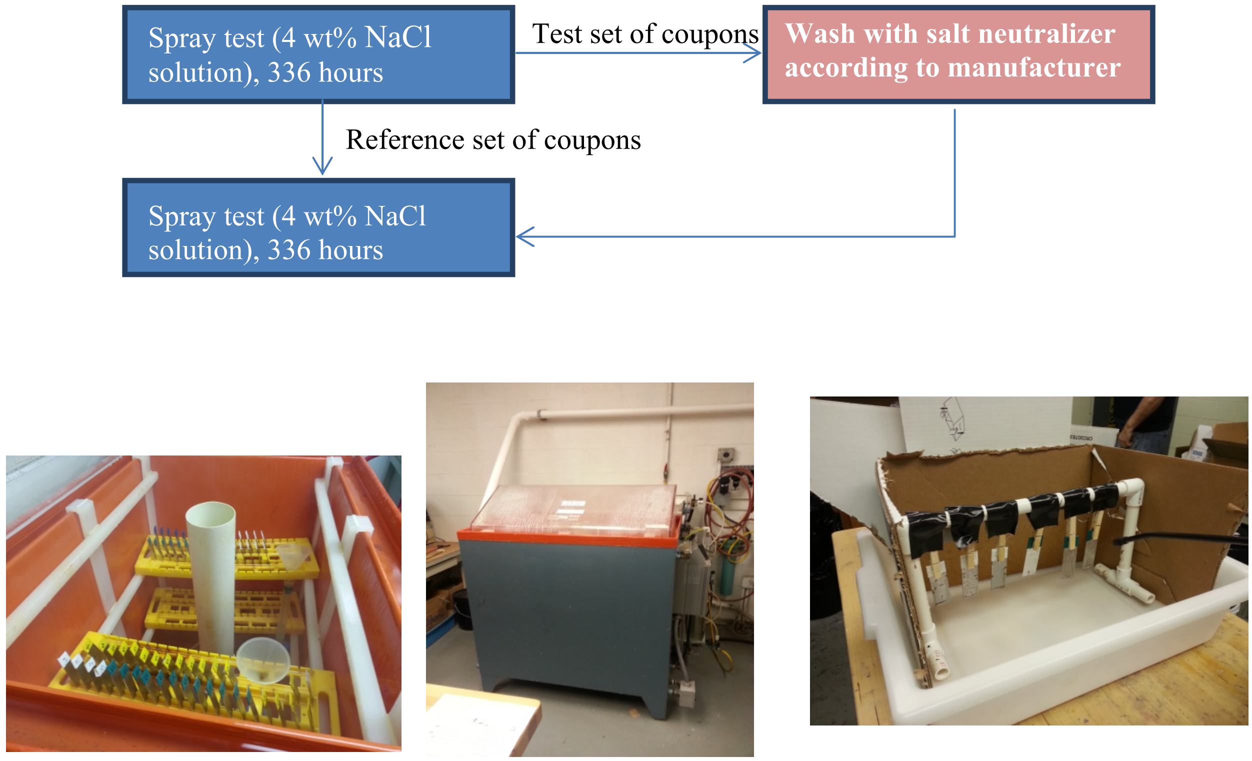


Figure 3-1A: Modified ASTM B117 test procedure for evaluating effectiveness of salt neutralizer solutions. B: Picture of salt spray chamber internals, picture of salt spray chamber, and picture of coupon washing.

3.2.2. Summary of Results for Accelerated Corrosion Testing on Bare Metals at Recommended Wash Concentrations

Initially, accelerated corrosion testing was conducted using the manufacturer's recommended dilutions (listed in Table 2-1). Table 3-1 contains the corrosion rate calculated for bare metal samples determined during the accelerated corrosion testing (ASTM B117) carried out in a controlled salt spray chamber. The results are listed for each metal at all washing conditions. Inhibitor efficiency was calculated compared to soap and water and conditions that inhibited corrosion are highlighted in yellow.

Table 3-1: Results from accelerated corrosion testing for six salt neutralizers and seven metal alloys at the manufacturer's recommended concentrations

Wash Conditions	Carbon Steel (A36)		Copper		Aluminum (2024T3)		Brass	
	Corrosion Rate (mmpy)	Inhibitor Efficiency (%)	Corrosion Rate (mmpy)	Inhibitor Efficiency (%)	Corrosion Rate (mmpy)	Inhibitor Efficiency (%)	Corrosion Rate (mmpy)	Inhibitor Efficiency (%)
BioKleen	2.22	-8%	0.17	-33%	0.05	36%	0.056	1%
ConSALT	2.57	-25%	0.21	-70%	0.10	-31%	0.086	-52%
Eastwood	2.45	-20%	0.21	-65%	0.04	49%	0.070	-24%
Neutro-wash	2.52	-22%	0.07	45%	0.03	56%	0.078	-38%
Salt-away	1.71	17%	0.10	20%	0.07	17%	0.050	12%
Winter Rinse	2.25	-10%	0.14	-12%	0.05	41%	0.064	-12%
Water and Soap	2.05	N/A	0.13	N/A	0.08	N/A	0.057	N/A
Water Only	2.18	N/A	0.16	N/A	0.06	N/A	0.060	N/A
Wash Conditions	Aluminum (5056)		Stainless Steel (410)		Stainless Steel (304)			
	Corrosion Rate (mmpy)	Inhibitor Efficiency (%)	Corrosion Rate (mmpy)	Inhibitor Efficiency (%)	Corrosion Rate (mmpy)	Inhibitor Efficiency (%)		
BioKleen	0.016	-41%	0.09	-91%	0.001	N/A		
ConSALT	0.043	-280%	0.06	-21%	0.007	N/A		
Eastwood	0.014	-20%	0.06	-13%	0.006	N/A		
Neutro-wash	0.002	84%	0.07	-40%	-0.002	N/A		
Salt-away	0.040	-251%	0.08	-67%	0.000	N/A		
Winter Rinse	0.012	-9%	0.06	-14%	0.002	N/A		
Water and Soap	0.011	N/A	0.05	N/A	0.000	N/A		
Water Only	0.011	N/A	0.03	N/A	0.000	N/A		

Figure 3-2 shows the percent reduction in corrosion compared to soap and water for each salt neutralizer. Copper, aluminum 2024T3, brass, and A36 carbon steel are shown in Figure 6 because these metals experienced a significant corrosion rate (> 0.06 mmpy). The other metals tested (aluminum (5056), stainless steel (304, 410)) had corrosion rates that were too low to compare differences in corrosion inhibition due to application of a salt neutralizer. Results indicate that the effectiveness of the salt neutralizer is alloy specific. For example, at the manufacturer's recommended wash concentrations Salt-away is the only salt neutralizer that prevents corrosion on all metals. Neutro-wash prevented corrosion on aluminum (2024T3) and copper; while Biokleen, Eastwood, and Winter Rinse prevented corrosion on aluminum (2024T3). Conversely, at the recommended dilution rates Biokleen, Eastwood, Neutro-wash, and Winter Rinse increased corrosion rate on at least one of the metals tested; while ConSALT increased corrosion rate on all metals tested.

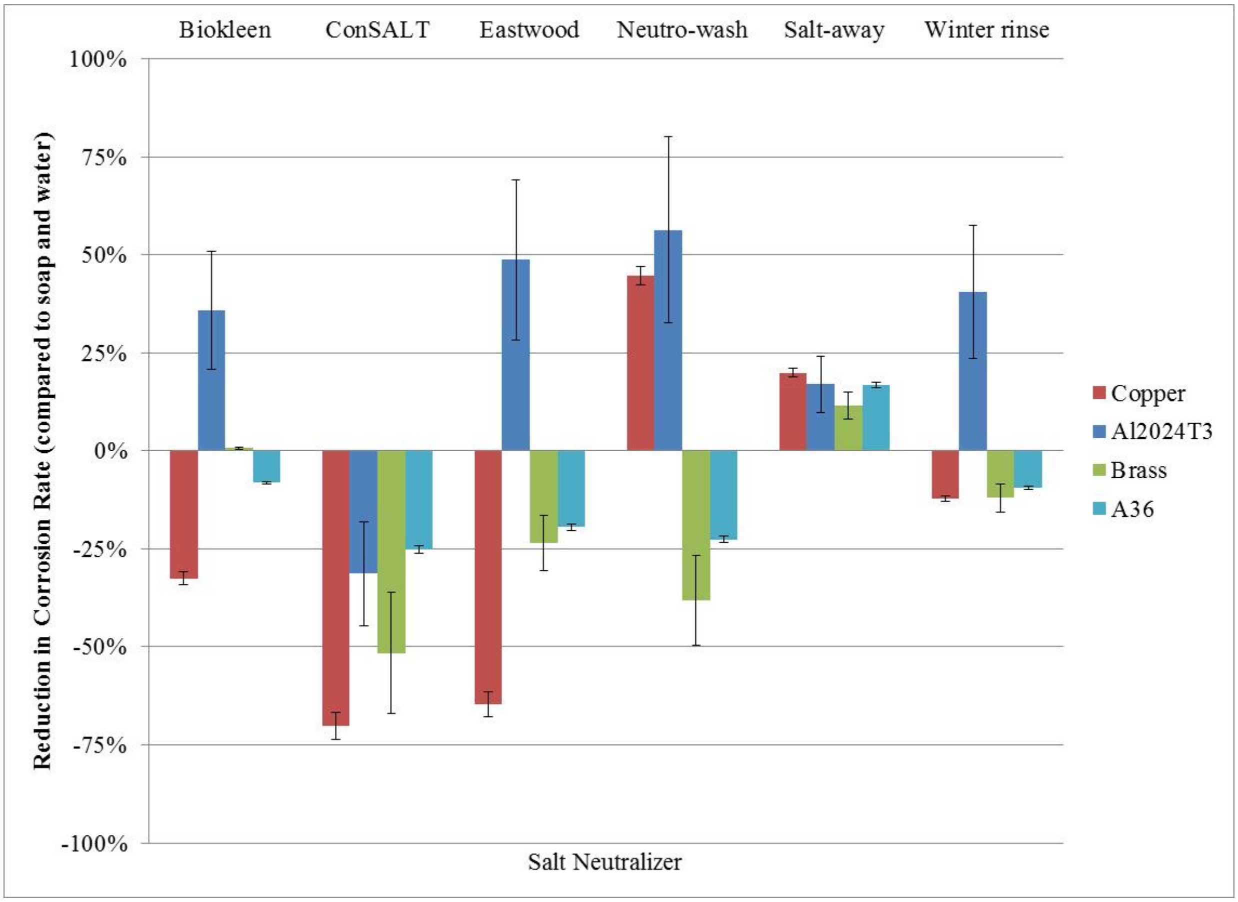


Figure 3-2: Percent reduction in corrosion for 6 salt neutralizers compared to soap and water. Notice that at the recommended dilution rates Salt-away inhibits corrosion on all metals tested; while, ConSALT accelerates corrosion on the samples tested.

3.2.3. Determination of Critical Micelle Concentration for Six Commercially Available Salt Neutralizers

Commercially available salt neutralizers contain a strong acid cleaner to remove corrosive chloride residue from the surface of the metal. However, the strong acid cleaner itself can be highly corrosive. Corrosion inhibitors, typically surfactants, are added to salt neutralizer to solutions to protect the metal surface during the washing process. Surfactants inhibit corrosion by forming a protective barrier at the surface of the metal. Therefore, corrosion inhibition of a salt neutralizer is directly related to the ability of the surfactant to aggregate at the metal surface. The critical micelle concentration (CMC) is defined as the concentration where surfactants in solution change their solvated state. At this surfactant concentration the majority of the physical and chemical properties undergo an abrupt variation. Below the CMC, the adsorption of the surfactant at the metal surface is minimal to moderate. Above the CMC, however, the metal surface becomes covered with a protective layer of surfactant monolayers. CMC is affected by a variety of factors such as ionic strength and temperature so it is imperative to determine the CMC for each wash system individually (Free 2012, Malik 2011).

The CMC of six salt neutralizers was measured by diluting them in a 3.5 wt.% sodium chloride (NaCl) via ultraviolet–visible (UV- Vis) spectroscopy in scan mode. A Thermo Scientific GENESYS 10S UV-Vis system was employed by detecting the absorbance peak of the salt neutralizer from concentrations of 0.01 to 20 v/v%. The samples are prepared in disposable semi micro UV-cuvettes from Brand by diluting the respective concentrations of salt neutralizer in 3.5 wt.% NaCl for a total volume of 1ml.

The CMC is determined by plotting absorbance vs. concentration (Figure 3-3a) at the wavelength where the peak for the surfactant is located (Figure 3-3b). The intersection of the two linear regressions is the value for CMC for the respective salt neutralizer.

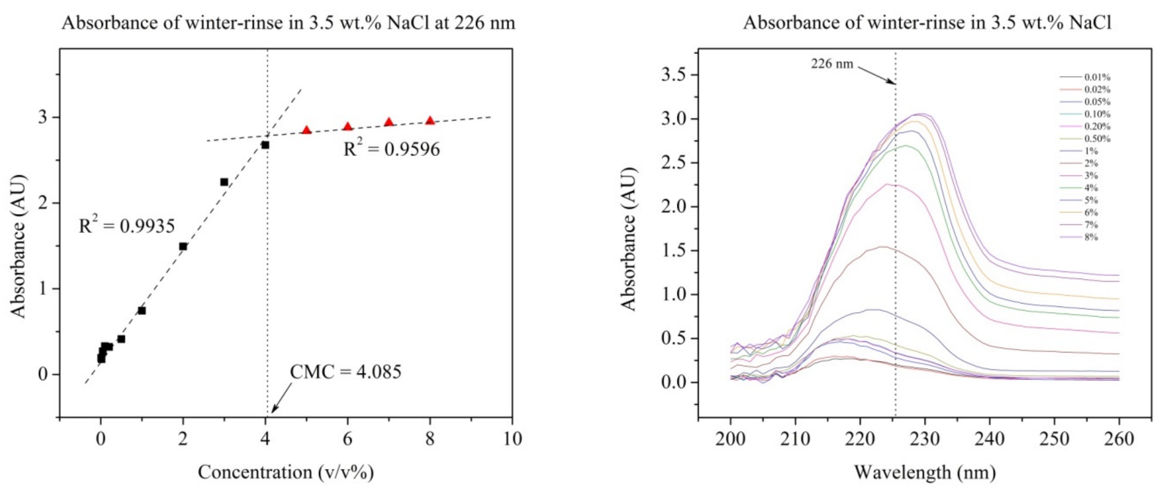


Figure 3-3: a) Plot of absorbance vs. concentration in v/v% of winter-rinse prepared in 3.5 wt.% of NaCl at a wavelength of 226 nm. b) Plot of absorbance vs. wavelength in nm of winter-rinse concentrations from 0.01 to 8 v/v% prepared in 3.5 wt.% of NaCl.

Table 3-2 shows CMC (vol. %) and the manufacturer's recommended washing dose (vol. %) for the commercially-available salt neutralizer solutions used in this study. Analysis of the salt neutralizer solutions showed that the more effective salt neutralizers determined during the accelerated corrosion testing also have recommended washing concentrations that are at or above their CMC; while the less effective salt neutralizers have recommended washing concentrations below their CMC. This indicates that salt neutralizers used at concentrations well above their CMC are more effective at preventing corrosion. This corrosion inhibition is most likely caused by the formation of a protective surfactant layer at the surface of the metal during cleaning. It is also possible that the surfactant layer remains after washing and further protects the metal surface during exposure to salt spray in the accelerated corrosion testing. Additionally, the surfactants will cause an increase in viscosity of the wash solution which will cause the wash to “cling” to the metal surface providing more time for salt removal.

Table 3-2: Critical micelle concentration for each salt neutralizer tested

Salt Neutralizer	**Critical Micelle Concentration (vol. %)**	**Recommended Washing Concentration (vol. %)**
BioKleen	3	3
ConSALT	14	10
Eastwood	4.5	5
Neutro-wash	5	11
Salt Away	3	10
Winter Rinse	4	4

3.2.4. Determination of Effective Adsorption Constant and Surfactant Surface Coverage

Initial experiments show that corrosion reduction is alloy and salt neutralizer specific. Therefore, analysis of the neutralizer/alloy interaction was conducted. Corrosion reduction of a salt neutralizer is thought to be directly related to the ability of the surfactant to aggregate at the metal surface and therefore wash concentration is extremely important. Below a critical wash concentration, the adsorption of the surfactant at the metal surface is minimal to moderate. Above the critical wash concentration, however, the metal surface becomes covered with a protective layer of surfactant monolayers if surfactant adsorption on the metal is thermodynamically favorable (Motamedi, 2013). The critical wash concentration for each salt neutralizer solution was determined using UV-vis analysis; while the surfactant surface coverage of the salt neutralizer was determined using electrochemical polarization. Surfactant surface coverage was calculated using the following equation:

$$\theta = 1 - \left(\frac{I_{inhib}}{I_{uninhib}}\right)$$

Where I_{unihib} is the corrosion current of a sodium chloride solution and I_{inhib} is the corrosion current in the presence of the salt neutralizer. Values of surfactant surface coverage were then fit using standard Langmuir-type isotherms:

$$\frac{C_i}{\theta} = \frac{1}{K_{eff}} + C_i$$

Where Ci is the surfactant concentration, K_{eff} is the effective adsorption-desorption equilibrium constant of the surfactant and can be calculated as the inverse of the intercept (Motamedi, 2013).

Table 3-3: Effective adsorption constants for 6 salt neutralizers and 4 metals determined using electrochemical polarization.

Salt Neutralizer	A36	Aluminum (2024T3)	Copper	Brass
	Effective Adsorption Constant (vol %)	**Effective Adsorption Constant (vol %)**	**Effective Adsorption Constant (vol %)**	**Effective Adsorption Constant (vol %)**
BioKleen	7	0.4	0.2	0.9
ConSALT	3	-	24	0.1
Eastwood	1	3	-	0.02
Neutro-wash	1	3	11	0.3
Salt-away	7	2	28	4
Winter Rinse	0.6	0.9	5	0.2

Effective adsorption-desorption equilibrium values for the salt neutralizer solutions used in this study are listed in Table 3-3. High values of K_{eff} suggest that the interaction between the surfactant molecule and the metal surface is strong and the adsorbed surfactant molecules are not easily removed from the metal surface. Analysis of polarization data shows that salt neutralizers high effective adsorption-desorption equilibrium values on a given metal surface also tended to prevent corrosion during accelerated corrosion testing. For example, accelerated corrosion testing showed that only Salt-away reduced corrosion rate on brass. Comparison to polarization data shows that only Salt-away has an effective adsorption-desorption constant greater than one.

This indicates that the other surfactant-brass interactions were not strong enough to withstand the cleaning process or the harsh conditions of the salt-spray chamber. On the other hand, the effective adsorption-desorption equilibrium constants for aluminum are greater than one, on average, and five of the six salt neutralizers tested reduced corrosion rate during accelerated corrosion testing. This further indicates that the surfactant/alloy interaction is critical in protecting the metal surface during the cleaning process or in the salt spray chamber.

Table 3-4: Surfactant surface coverage at various wash concentrations for 6 salt neutralizers

Salt Neutralizer	**CMC (vol. %)**	**Surfactant Surface Coverage (θ)**	**Recommended Concentration (vol. %)**	**Surfactant Surface Coverage (θ)**	**2.5 x CMC (vol. %)**	**Surfactant Surface Coverage (θ)**
BioKleen	3	0.95	3	0.95	16	0.99
ConSALT	14	0.93	10	0.92	35	0.99
Eastwood	4.5	0.83	5	0.83	12	0.90
Neutro-wash	5	0.83	11	0.91	13	0.91
Salt-away	3	0.91	10	0.92	9.8	0.92
Winter Rinse	4	0.76	4	0.76	10	0.88

Copper and A36 carbon steel show high Keff values. However, not all salt neutralizers prevent corrosion at the manufacturer's recommended concentrations for these metals. This indicates that concentration may also play a role on corrosion reduction. Table 3-4 shows the surfactant surface coverage (θ) on A36 for the six salt neutralizers used in this study at their critical wash concentration, manufacturer's recommended wash concentration, and 2.5 times the critical wash concentration (vol. %). Carbon steel was chosen (A36) because it exhibited the highest corrosion rate of all metals tested initially. Analysis of the salt neutralizer solutions showed that the more effective salt neutralizers determined during the accelerated corrosion testing also have recommended wash concentrations that are at or above their critical wash concentration; while the less effective salt neutralizers have recommended wash concentrations at or below their critical wash concentration. This increase in corrosion inhibition is most likely due to the increase in surface coverage; however, an increase in the concentration of the cleaning agent could also increase corrosion inhibition. Overall, salt neutralizers used at concentrations well above their critical wash concentration may be more effective at preventing corrosion.

3.2.5. Summary of Results for Accelerated Corrosion Testing on Bare Metals at Increased Wash Concentrations

Accelerated corrosion testing (ASTM B117) was then conducted at wash concentrations of 2.5 times the CMC (listed in Table 3-2) using carbon steel (A36). Carbon steel was chosen because it exhibited the highest corrosion rate of all metals initially tested. Figure 3-4 shows the percent reduction in corrosion compared to soap and water for each salt neutralizer. Notice that at wash dilutions of 2.5 times the CMC, all of the salt neutralizers prevent corrosion on carbon steel compared to soap and water. This corrosion prevention is most likely caused by both the increased surfactant layer and the increased strong acid concentration. These results indicate that the effectiveness of the salt neutralizer solution is also concentration specific.

To determine the effect of an increase in strong acid concentration on the overall corrosion prevention, a five weight percent sulfamic acid solution was tested. The five weight percent sulfamic acid solution reduced corrosion rate by 10% (shown as a red line on Figure 7). Biokleen and Salt-away reduce corrosion by a rate that is much higher than acid alone. Therefore, it is concluded that the additional corrosion inhibition is most likely caused by an increase in surfactant concentration. Neutro-wash, Eastwood, Winter Rinse, and ConSALT all show corrosion reduction that is approximately 10%; therefore, it is hypothesized that for these salt neutralizers the surface is protected during cleaning but there is not likely to be an added benefit from the protective surfactant layer after cleaning.

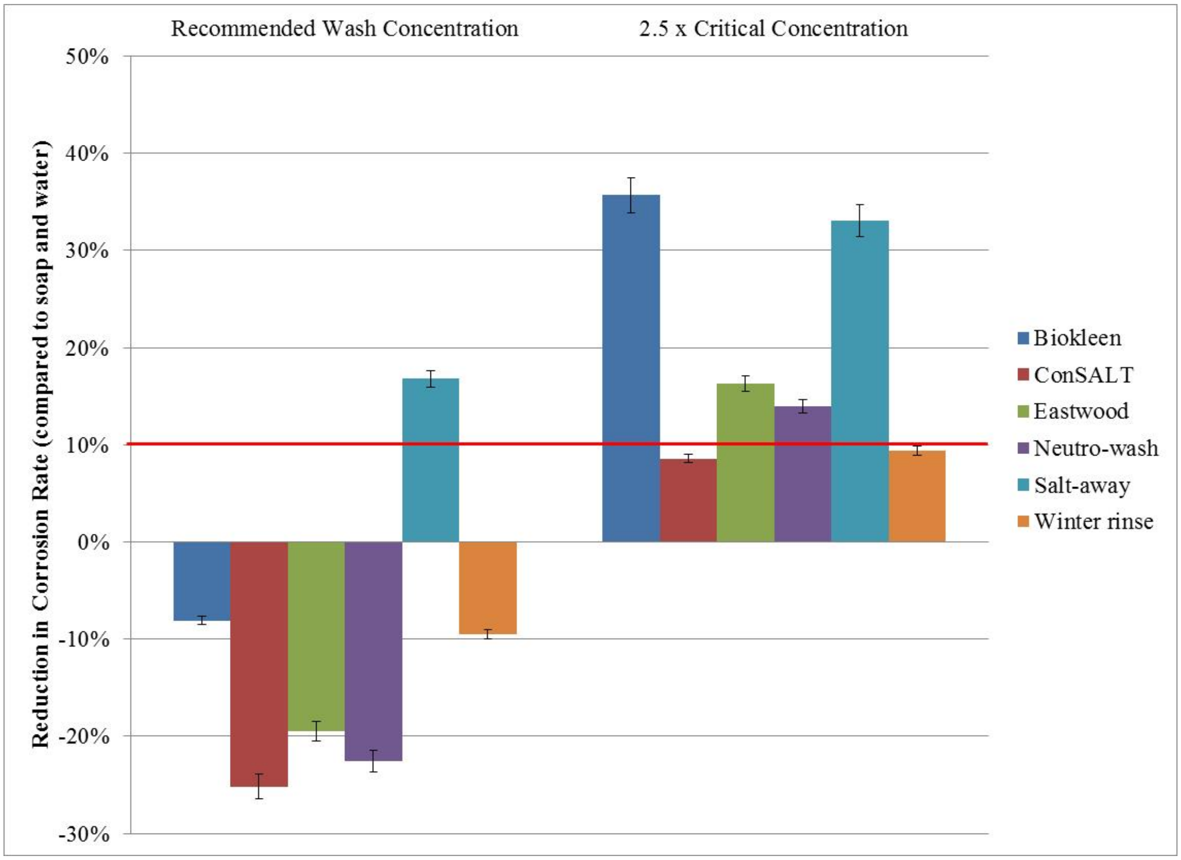


Figure 3-4: Corrosion inhibition for salt neutralizer solutions on carbon steel (A36) at the recommended wash concentration and wash concentrations that are 2.5 times the critical micelle concentration.

3.2.6. Characterization and Analysis of Bare Metal Surfaces

3.2.6.1. Contact Angle Measurements

The affinity of salt neutralizers on a metal surface can be quantified by measuring the wettability of the metal surface via contact angle measurements. Metals were bought from Metal Samples (Munford, AL, USA) and were used as received (glass bead blasted finish) wrapped in a volatile corrosion inhibitor (VCI) paper.

Before testing metal samples (coupons) were submerged for 6 hours in each salt neutralizer (Biokleen, ConSALT, Eastwood, Neutro-wash, Salt-away and Winter Rinse) solution at their recommended wash concentrations, the surface is washed with the DEAD treatment (DI water, ethanol, acetone, DI water) to ensure the removal of any volatile organic content on the metal before immersion. Coupons are removed from the solution and were left to air-dry overnight.

Contact angles were measured using the drop shape analyzer DSA20E from KrüssUSA (Matthews, NC, USA). The sessile drop fitting method was used where a drop of 5 µL total volume of water is placed onto the sample surface by a micro-syringe pointed vertically.

Table 3-5: Results from contact angle measurements for carbon steel (A36) after 6 hour immersion at recommended wash concentration for six salt neutralizer solutions

	Contact Angle
Bare Metal	55°
BioKleen	20°
ConSALT	30°
Eastwood	75°
Neutro-wash	70°
Salt-away	0°
Winter Rinse	75°

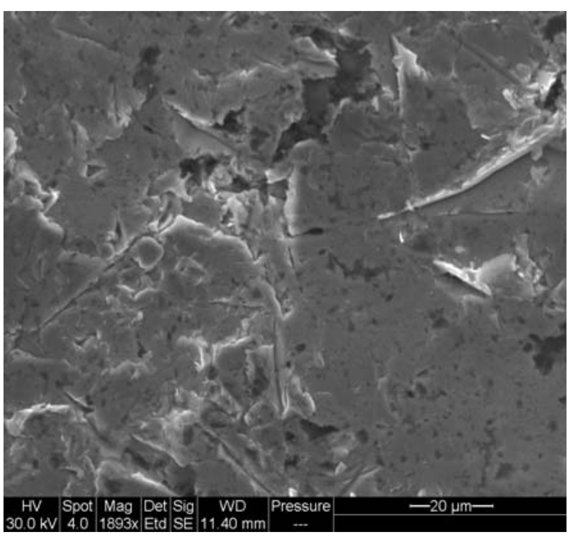
Results from the contact angle measurements can be seen in Table 3-5. Contact angle for carbon steel was measured after a 6 hour immersion in salt neutralizer solution at the manufacturer's recommended concentration. An increase in contact angle shows that the bare metal surface has become more hydrophobic; while, a decrease in contact angle shows that the bare metal surface has become more hydrophilic. A comparison of the contact angles in Table 3-5 shows that the change in surface properties is dependent on surfactant type. Surfactants are typically amphiphilic compounds, meaning they contain hydrophilic heads and hydrophobic tails, and are categorized by the charge on the charge on their head group. For example, cationic surfactants have positively charged functional groups on their hydrophilic head; while, anionic surfactants have negatively charged functional groups.

Results indicate that each salt neutralizer tested uses a different surfactant as a corrosion inhibitor. For example, BioKleen, ConSALT, and Salt-away decrease the contact angle of the metal surface, making the surface more hydrophilic. This decrease in contact angle is caused by an anionic surfactant. When the surfactant comes into contact with the negatively charged metal surface the charged head is repelled from the surface, making a negatively charged layer on the surface and increasing hydophilicity. Conversely, Eastwood, Neutro-wash, and Winter Rinse increase the contact angle on the metal surface. This increase in contact angle is caused by either a cationic or nonionic surfactant. When these types of surfactants come into contact with the negatively charged metal surface, the charged head is attracted to the surface and the hydrophobic tail creates an organic layer at the metal surface. This organic layer causes the surface to become more hydrophobic. A survey of the literature shows that, as indicated by this work, the most effective type of surfactant is dependent on the metal surface of interest.

3.2.6.2. SEM/EDX Analysis

The evaluation of the metal surface after corrosion is performed via scanning electron microscopy (FEI Quanta 200) coupled with energy-dispersive X-ray spectroscopy from EDAX (SEM/EDX) for chemical element identification.

Metal samples were analyzed using a conventional tungsten electron source at magnifications of up to 20000x at high voltage (30 KV) and spot size 4.0 using the xT microscope control software for visualization of the images and the EDAX Genesis software for element analysis.



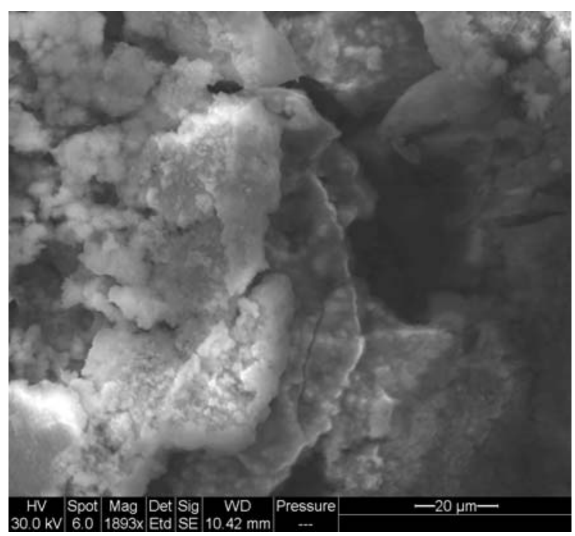


Figure 3-5: SEM images of carbon steel (A36) before (left) and after (right) accelerated corrosion testing. The image on the right shows the metal surface after 48 hours of salt spray exposure with 4 Salt-away washes.

The morphology of the carbon steel (A36) samples before and after 48 hours of salt spray exposure is shown in Figure 3-5. The image on the left depicts the initial bare metal coupon; while, the image on the right shows the surface morphology of the bare metal after 48 hours of salt exposure with 4 Salt-away washes. The surface morphology of the bare metal sample after salt spray exposure shows that there is an iron oxide layer being formed. This is corroborated by EDX analysis. Table 3-6 shows the results from EDX analysis for A36 analysis after 48 hours of salt spray testing with 4 salt neutralizer washes. The initial metal is 97.5% iron with the balance silicon. However, after 48 hours in the salt spray chamber, the weight percent of oxygen on the metal surface has increased. This shows that there is an iron oxide corrosion product being formed on the metal surface.

Table 3-6: EDX analysis for SEM samples after salt spray testing for six salt neutralizers

	Weight Percent on Surface		
	Fe	**O**	**Si**
Bare Metal	97.50	-	2.50
BioKleen	24	76	-
ConSALT	27	73	-
Eastwood	23	77	-
Neutro-wash	20	79	-
Salt-away	33	67	-
Winter Rinse	Not Available		

The morphology of the carbon steel (A36) surface before and after 48 hours of salt spray exposure was then compared to the surface morphology of the metal after 6 hour immersion in salt neutralizer. It is clear that the salt neutralizers form a uniform surfactant layer on the surface of the metal. Salt-away, unlike the other surfactants, appears to form a thick film on the surface. This can be corroborated by referring to EDX analysis shown in Table 3-7. For Salt-away, the surface contains phosphorus, sodium, calcium and potassium in addition to iron and oxygen. These elements are common in anionic surfactants, further proving that the decrease in contact angle from Salt-away is caused by an anionic surfactant.

Table 3-7 also shows that the level of oxygen present at the surface of the metal has increased for the other five surfactants tested. This increase in oxygen may be caused by the formation of corrosion products or the presence of the surfactant layer. Comparison of the immersed samples to the samples from salt spray exposure, show a different surface morphology. This indicates that the increase in oxygen is most likely caused by a protective surfactant layer on the metal surface. Additionally, these SEM images match previously published SEM images of surfactant layers on metal surfaces.

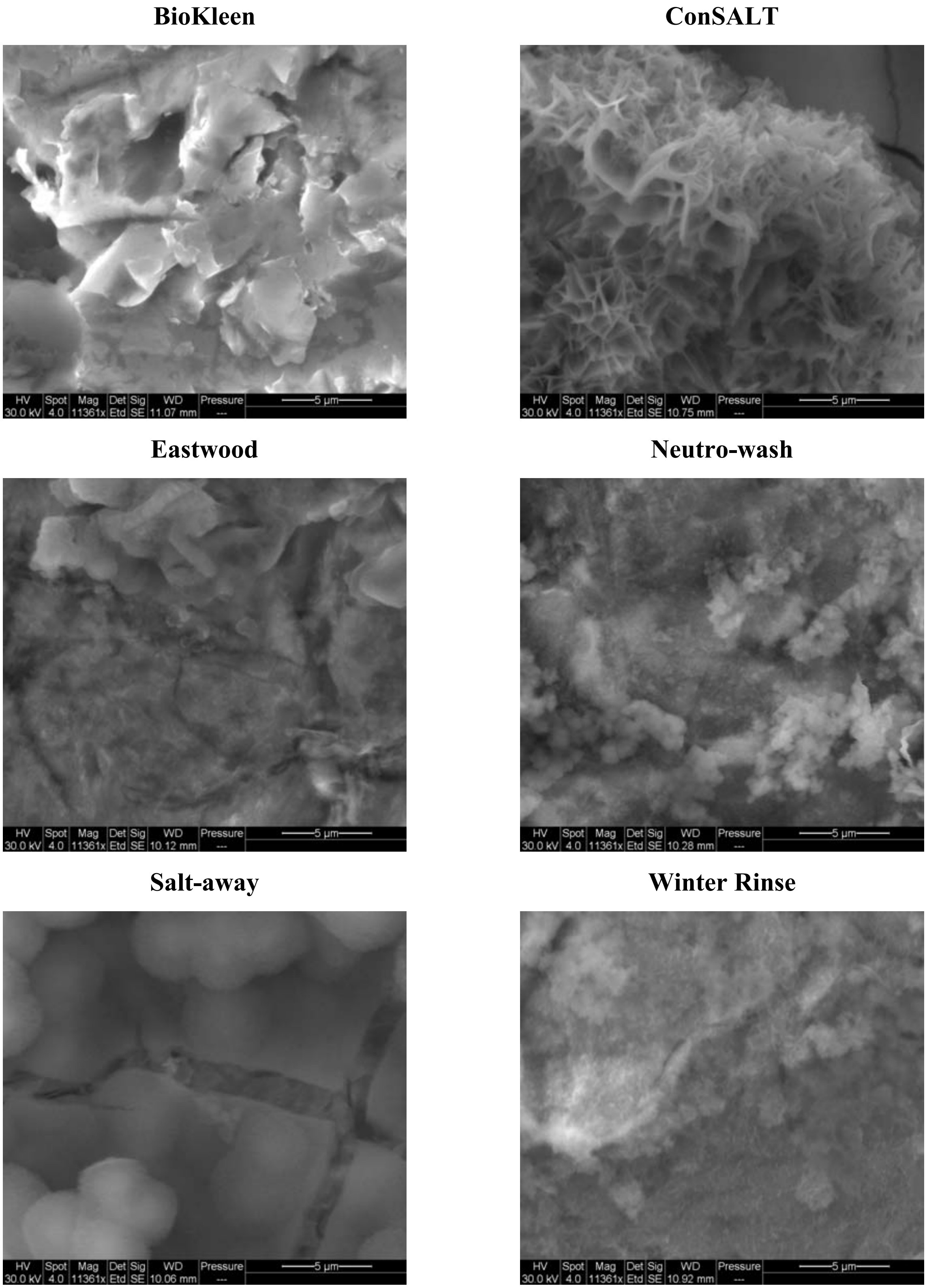


Figure 3-6: SEM images of carbon steel after 6 hour immersion testing in six salt neutralizer solutions (Motamedi, 2013).

Table 3-7: EDX analysis for SEM samples after 6 hour immersion in six salt neutralizer solutions

	Weight Percent on Surface					
BioKleen	Fe 87.43	O 5.96	Si 6.62			
ConSALT	Fe 65.38	O 33.74	Cl 0.88			
Eastwood	Fe 90.37	O 7.86	Si 1.76			
Neutro-wash	Fe 73.97	O 15.37	Si 9.65	Ca 1.01		
Salt-away	Fe 66.71	O 19.02	Na 3.54	P 9.54	K 0.81	Ca 0.91
Winter Rinse	Fe 93.08	O 6.92				

3.3. Overview of Effectiveness of Salt Neutralizers at Reducing Corrosion on Bare Metals

- On all bare metal surfaces tested (seven total) at manufacturer-recommended neutralizer dilution (i.e. gallons of concentrated product per gallon of water), only Salt-Away reduced or had minimal impact on the corrosion rate compared to soap and water (Table 3-1).
- Neutro-Wash had mixed results at manufacturer-recommended neutralizer dilution. Neutro-Wash increased the corrosion rate for carbon steel (A36), copper, and brass but reduced the rate for copper and aluminum (Table 3-1).
- Many of the commercial neutralizer solutions actually increased the rate of corrosion (Table 3-1), especially for carbon steel (A36) and copper, two metals of particular concern to ODOT.
- Increasing the neutralizer dose to a value greater than that recommended by the manufacturer made all of the neutralizers effective at reducing the corrosion rate on

carbon steel (Figure 3-4). However, this will significantly reduce the cost-effectiveness of neutralizer application. Salt-Away and BioKleen reduced the corrosion rate by more than 30%.

CHAPTER IV

EVALUATION OF SALT NEUTRALIZER SOLUTIONS AT PREVENING CORROSION ON COATED METAL SAMPLES

4.1. Introduction

To evaluate the effectiveness of salt neutralizers on preventing corrosion of coated metal samples, accelerated corrosion testing was again performed to compare effectiveness of washing methods compared to water and soap. The three overall, top-performing salt neutralizers, as determined in Chapter 3, were used to wash coated metal samples. Effectiveness of the salt neutralizer to prevent corrosion on a coated metal sample was evaluated using the standard ASTM D1654-08 procedures including visual inspection of the gloss and color of the coating, counting the number of defects and holidays on the surface, pull off adhesion, and a pencil scratch test. The amount of rust creepage was the main test for the effectiveness of the salt neutralizer and coating at corrosion prevention on scribed coated surfaces. Additionally, electrical impedance spectroscopy (EIS) testing was performed to determine the degradation of the coating after exposure to salt spray. Accelerated corrosion testing was again performed with the help of Ben Curatolo, Ph.D. at Light Curable Coatings in Berea, OH. Similar to the results obtained for bare metal samples, results indicate that corrosion prevention is alloy, coating, and neutralizer specific.

4.2. Experimental Procedure for Evaluating the Performance of Coatings in the Presence of Salt Neutralizer

4.2.1. Procedure for Coatings Application

Testing on coated metal samples was performed using the three salt neutralizers shown to be the most effective at preventing corrosion on bare metal samples at the manufacturer's recommended wash concentration on mild carbon steel (A36), aluminum (2024T3, 5086), and stainless steel (304L, 410). A parallel study of three commercially available coatings was carried out for comparison: LubraSeal, Light-curable Coatings, and OEM paint.

Solvent-free UV curable coatings were sprayed onto panels with a conventional air pressure touch-up spray gun, SPEEDAIRE brand, model number 4RR06 with 1.8 mm tip size, and each layer of coating was UV cured individually. For aluminum alloy panels, approximately 1 mil of LCCOAT™ Gray Primer 021 was applied and UV cured, and then approximately 2 mils of LCCOAT™ Black 203 topcoat was applied and UV cured.

For stainless steel panels and steel panels, approximately 1 mil of LCCOAT™ Gray Primer 022 was applied and UV cured, and then approximately 2 mils of LCCOAT™ Black 203 topcoat was applied and UV cured. Spray application of Lubra-Seal, a polymer encapsulant (Rhomar Industries, Springfield, MO, USA), and Dupli-color (The Sherwin-Williams Company, Cleveland, OH, USA) spray automotive paint (gray primer, universal black automotive paint, clear top finish) were applied using the manufacturer's specifications and procedures. Table 4-1 lists the hardness and adhesion for the coatings before accelerated corrosion testing.

Table 4-1: Properties (adhesion and hardness) of three tested coatings before accelerated corrosion testing.

	Hardness	Adhesion				
		A36	AL2024T3	AL5086	304	410
LubraSeal	9B	5B	5B	5B	5B	5B
Light-curable Coating	9H	4B	1B	2B	1B	4B
OEM paint	B	4B	-	-	-	-

4.2.1. Experimental Procedure Experimental Procedure for the Determination of Coating Rating on Scribed Coated Samples

Coated panels were scribed with a computerized New Hermes Vanguard 3400 Engraver. Scribe line depth was 0.008 inch and scribe line width was also 0.008 inch. Effectiveness of the salt neutralizer to prevent corrosion on the coated samples was evaluated using the standard ASTM D1654-08 procedures including visual inspection of the gloss and color of the coating, counting the number of defects and holidays on the surface, pull off adhesion, and a pencil scratch test. The amount of rust creepage from the scribe was the main test for the effectiveness of the salt neutralizer and coating at corrosion prevention (Table 4-2).

Table 4-2: Representative coating rating based on mean creepage from scribe (mm) from ASTM D1654-08 standard.

Representative Mean Creepage from Scribe (mm)	Coating Rating
Zero	10
Over 0 to 0.5	9
Over 0.5 to 1.0	8
Over 1.0 to 2.0	7
Over 2.0 to 3.0	6
Over 3.0 to 5.0	5
Over 5.0 to 7.0	4
Over 7.0 to 10.0	3
Over 10.0 to 13.	2
Over 13.0 to 16.0	1
Over 16.0	0

4.2.2. Experimental Procedure for the Determination of Coating Rating on Unscribed Coated Samples

Effectiveness of the salt neutralizer to prevent corrosion on the coated samples was evaluated using the standard ASTM D1654-08 procedures based on area of the coating that failed after salt spray testing (

Table 4-3). Coated metal samples were in the salt spray chamber for a total of 264 hours treating coupons at 6, 24, 48, 72, 96, 168, 192, 216 and 240 hours after initial setup. Spraying/rinsing with water and drying the samples with laboratory cleaning tissues before wrapping them in the same paper.

Table 4-3: Representative coating rating based on area failed on an unscribed coated surface from ASTM D1654-08 standard.

Area Failed (%)	Coating Rating
No failure	10
0 to 1	9
2 to 3	8
4 to 6	7
7 to 10	6
11 to 20	5
21 to 30	4
31 to 40	3
41 to 55	2
56 to 75	1
Over 75	0

4.2.3. Experimental Procedure for EIS testing on Unscribed Samples

The performance of the coated metals was evaluated by electrochemical impedance spectroscopy (EIS) using a Gamry (Warminster, PA, USA) - Reference 600 Potentiostat/Galvanostat/ZRA and the electrochemical cell shown in Figure 4-1. The metal sample is clamped to the glass cell body using an O-ring in the interface of the metal surface to avoid any leaks from the system and separated by an insulator in the bottom. The cell contains a silver/silver chloride (Ag/AgCl) reference electrode from BASi (West Lafayette, IN, USA) and a graphite counter electrode. The electrolyte used for the experiments is 3.5 wt.% sodium chloride (NaCl). This solution is placed in the glass cell to enter in contact with the coated surface of the sample. A Faraday cage is used to cancel any current or voltage noise that can be transferred to the system.

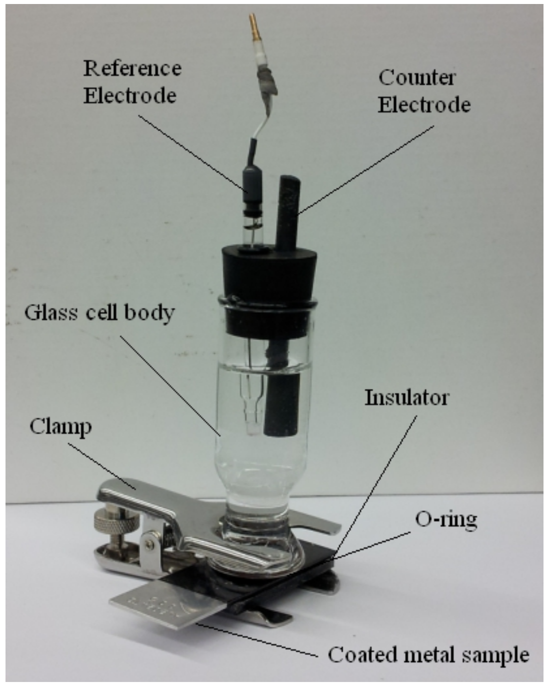


Figure 4-1: Electrochemical cell used for EIS measurements of coated metal samples

The current is measured by applying an AC voltage of 10 mV amplitude (rms) vs. the open circuit potential measured after 100 seconds, with a frequency range of 10 kHz to 10 mHz with ten points per decade. The software Gamry Echem Analyst Version 6.11 was utilized to analyze the EIS results. Figure 4-2 shows theoretical impedance spectra for good, intermediate, and poor coating quality by plotting resistance (Z) versus frequency (Hz).

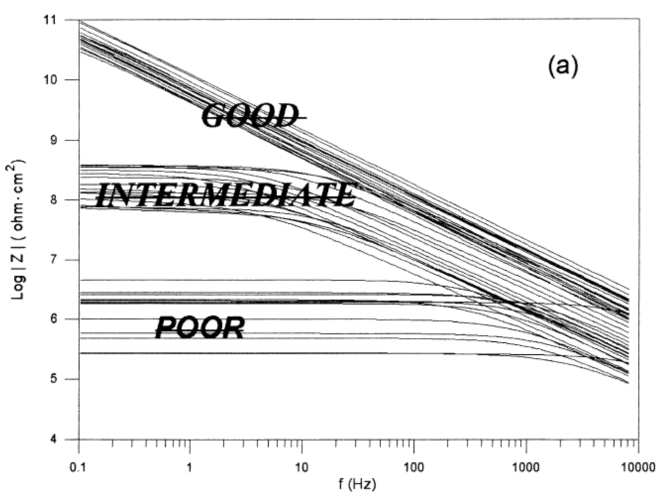


Figure 4-2: Theoretical impedance spectra used as training sets for good, intermediate and poor coating quality by plotting Z vs. frequency (Lee, 1998).

4.3. Summary of Results for Accelerated Corrosion Testing on Coated Samples

4.3.1. Summary of Creep Results for Scribed Samples

Representative mean creep from the center of the scribe was determined for three coatings on five metal alloys. Results of creep on A36 can be seen in Table 4-4 for the three overall, top-performing salt neutralizers determined by bare metal testing. The creep on all other metals tested was zero (see APPENDIX B), indicating that the coating successfully prevented corrosion on the metal surface.

Table 4-4: Summary of creep results, coating rating, and corrosion inhibition for scribed samples on A36. Results were obtained for three salt neutralizers, water and soap, and water only. Corrosion inhibition is determined with respect to soap and water.

		Scribed Samples		
		Creep (mm)	**Coating Rating**	**Corrosion Inhibition (%)**
LubraSeal	Eastwood	1.21 ±0.04	7	N/A
	Neutro-wash	1.10±0.24	7	N/A
	Salt-away	1.15±0.31	7	N/A
	Soap and Water	1.22±0.29	7	N/A
	Water only	1.15±0.19	7	N/A
Light-curable Coating	Eastwood	0.70±0.10	8	34%
	Neutro-wash	1.22±0.38	7	-15%
	Salt-away	0.76±0.06	8	28%
	Soap and Water	1.06±0.36	7	N/A
	Water only	0.83±0.17	8	N/A
OEM Paint	Eastwood	1.06±0.04	7	N/A
	Neutro-wash	1.08±0.23	7	N/A
	Salt-away	1.09±0.19	7	N/A
	Soap and Water	1.03±0.25	7	N/A
	Water only	1.32±0.16	7	N/A

Notice that for LubraSeal and OEM paint, there was little deviation in creep rate and coating rating between the coatings and wash conditions. For LCC, however, Salt-away and Eastwood reduced creep by 28 and 34%, respectively. These results indicate that, similar to bare metal samples, corrosion prevention on coated metal samples is both surface and neutralizer specific. An example of a scribed sample after salt spray exposure can be seen in Figure 4-3.

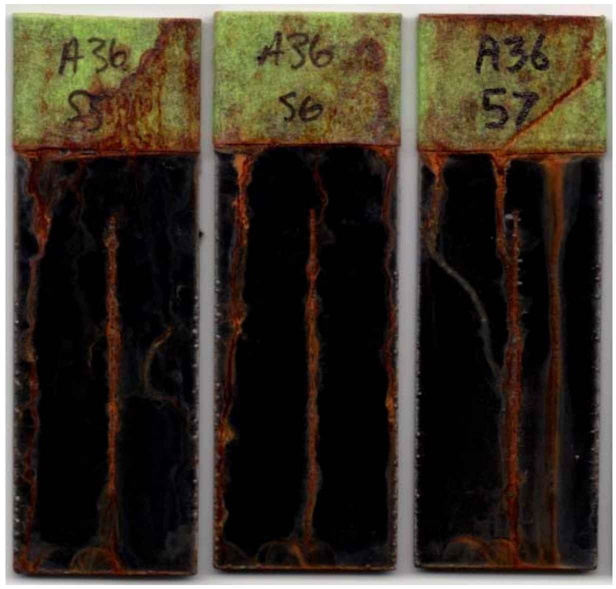


Figure 4-3: Photograph of scribed sample (LCC on A36 with Salt-away wash) after 7 days of salt spray exposure. Creep (mm) was determined as distance from the scribe of coating failure or corrosion.

4.3.2. Summary of Results for Coating Rating on Unscribed Samples

Photographs of the coated A36 metals samples after 14 days in the salt spray chamber are shown in Figure 4-4. Notice that LCC shows limited areas with corrosion or coating failures. LubraSeal, however, shows a large amount of corrosion on the metal surface; while, OEM paint shows a large number of areas of blistering or coating failure on the surface.

Table 4-5 shows the summary of coating rating based on failed area of the coating using the rating shown in Table 4-3. Unlike the results for the scribed coatings, the unscribed coatings show significant variability between coatings, alloy, and wash methods. Referring to Table 4-5, LCC has the highest coating rating, on average; while, LubraSeal has the lowest average coating rating. Comparison between salt neutralizers becomes more complicated, as effectiveness appears to be a function of coating and metal alloy. For example, Eastwood is effective at preventing coating failure for LubraSeal coated on aluminum and stainless steel; while it appears to be ineffective at preventing coating failure for LubraSeal coated on mild steel. Similarly to results from the scribed coated samples, Eastwood and Salt-away appear to be effective at preventing coating failure for LCC. These results further illustrate the complexity of determining an effective corrosion prevention strategy, as there is not one salt neutralizer combination that is effective at preventing corrosion or coating failure for all coating/alloy combinations.

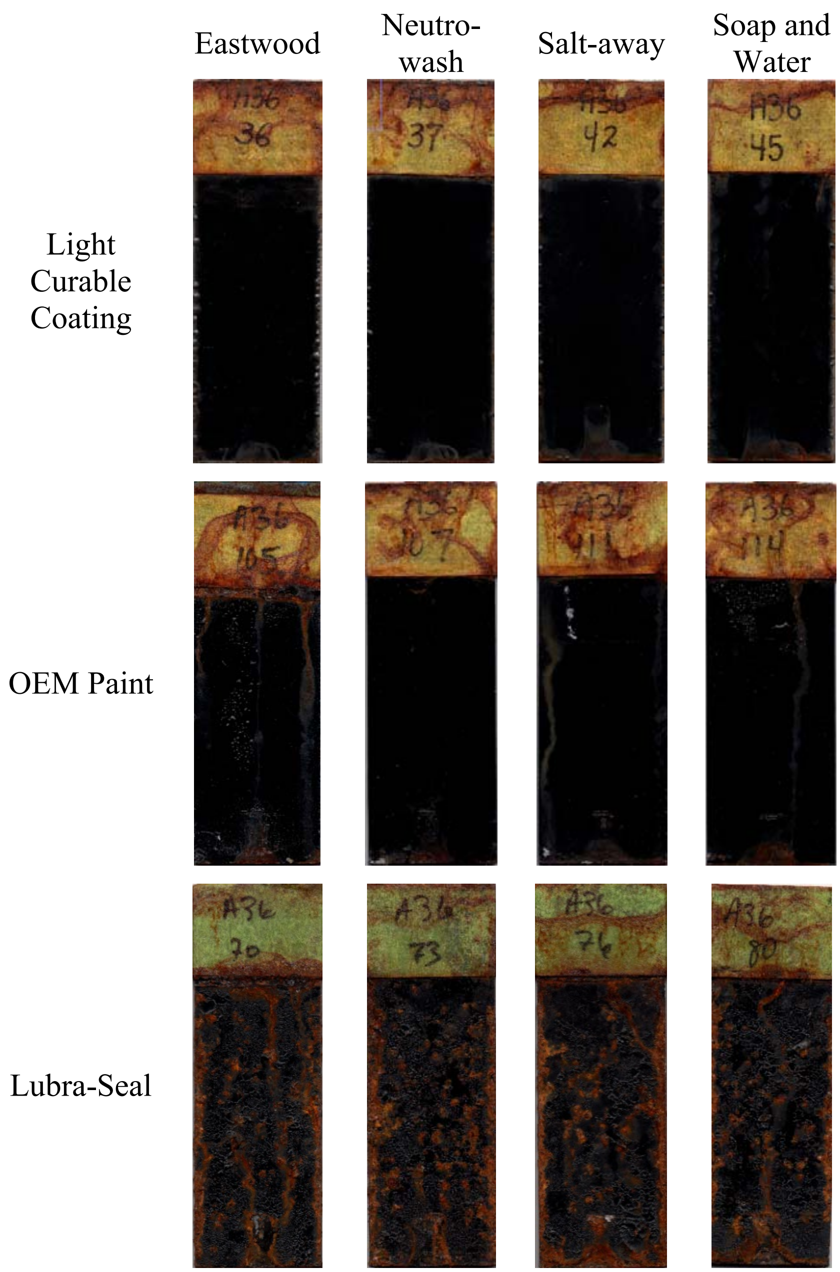


Figure 4-4: Photographs of coated samples (A36) after 14 days of salt spray exposure.

Table 4-5: Summary of coating rating for unscribed samples after accelerated corrosion testing. Results were obtained for three salt neutralizers, water and soap, and water only.

		Mild Steel (A36)	**Aluminum (2024T3)**	**Aluminum (5086)**	**Stainless Steel (304L)**	**Stainless Steel (410)**
Lubra Seal	Eastwood	1	9	9	9	7
	Neutro-wash	2	8	8	8	6
	Salt-away	4	7	8	9	6
	Soap and Water	3	7	7	7	5
	Water	2	7	7	7	6
LCC	Eastwood	8	9	9	9	8
	Neutro-wash	8	9	9	9	8
	Salt-away	8	9	9	10	8
	Soap and Water	7	9	9	10	7
	Water	8	10	10	9	9
OEM Paint	Eastwood	4	-	-	-	-
	Neutro-wash	2	-	-	-	-
	Salt-away	2	-	-	-	-
	Soap and Water	4	-	-	-	-
	Water	2	-	-	-	-

4.3.3. Summary of Results for EIS analysis of Coated Samples

Visual inspection of the coatings can be subjective and does not provide any information about what is happening below the surface of the coating at the metal/coating interface. Electrical impedance spectroscopy can be used to determine the protective ability of the coating as well as to determine the amount of water being absorbed into the coating layer through determination of pore resistance. A decrease in pore resistance is indicative of an increase in the amount of conductive water molecules in the coating layer (Olivier and Poelman, 2012). Experiments were carried out using the procedure described in section 4.2.3. The resistance of the coating was determined before and after accelerated corrosion testing using Simplex fitting.

Salt neutralizers that maintain or increase the initial pore resistance of the coating are deemed effective at corrosion prevention on the surface of the coating.

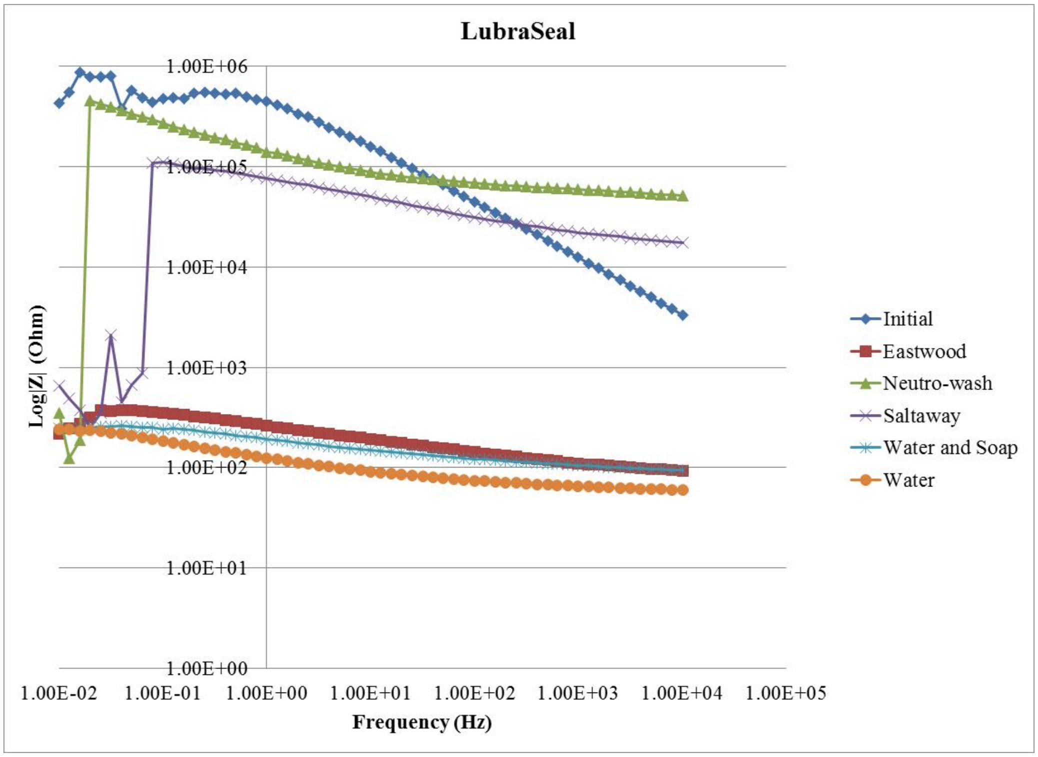


Figure 4-5: Bode plot for LubraSeal on A36 before and after 14 days of salt spray exposure for three salt neutralizers.

EIS analysis for LubraSeal coated A36 coupons is shown in Figure 4-5. Referring to Figure 4-2, initially the LubraSeal coating provides intermediate levels of corrosion protection. After 14 days of salt spray exposure, Neutro-wash and Salt-away show moderate levels of corrosion protection; while, Eastwood, water and soap, and water only show poor levels of corrosion protection. Calculated values of pore resistance can be found in Table 4-6. Values of pore resistance below 10^5 Ohm cm^2 are considered to be an indication of poor coating quality as well as the uptake of large amounts of water into the coating layer. Notice that all of the salt neutralizers tested on LubraSeal coated A36 show poor coating quality after salt spray testing; however, Salt-away and Neutro-wash show the highest pore resistance. These results validate visual inspection where Salt-away, Neutro-wash, and water and soap had the highest coating rating of the LubraSeal coated coupons.

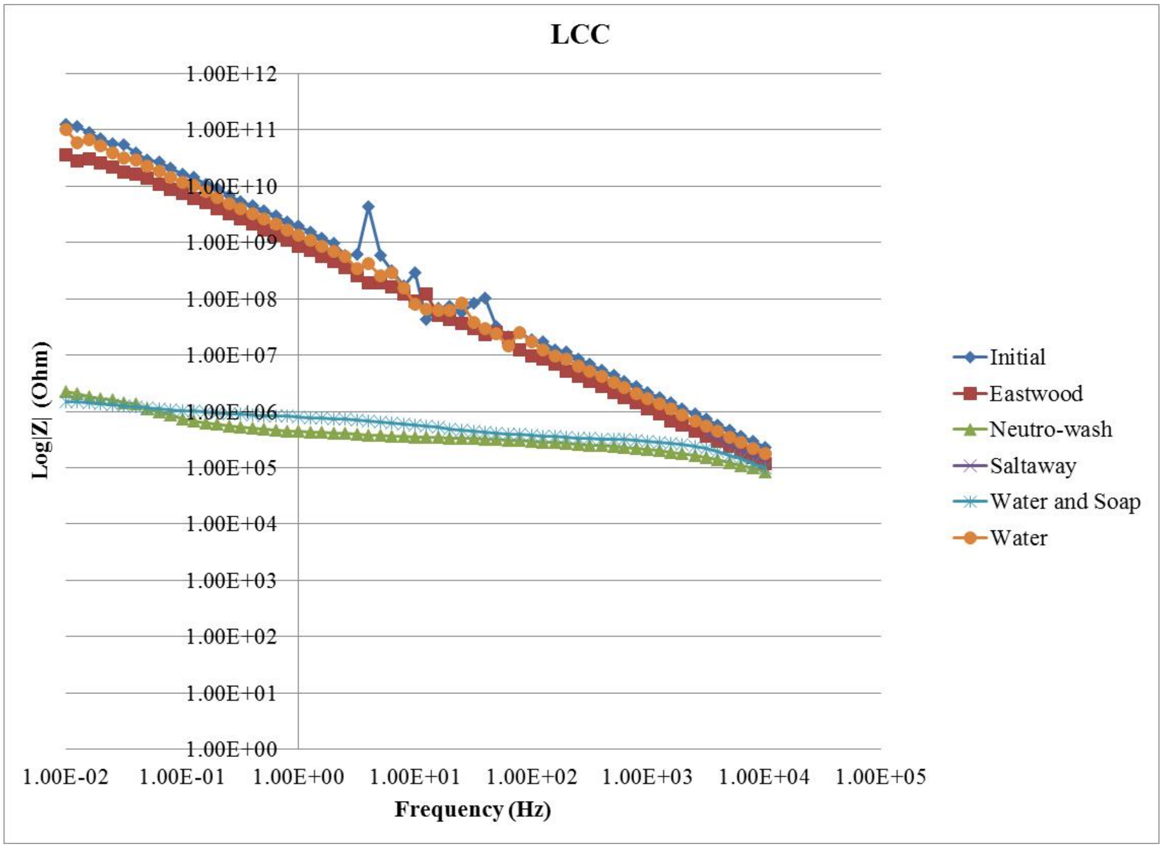


Figure 4-6: Bode plot for LCC on A36 before and after 14 days of salt spray exposure for three salt neutralizers.

EIS analysis for LCC coated A36 coupons is shown in Figure 4-6. Referring to Figure 4-2, initially the LCC coating provides a good level of corrosion protection. After 14 days of salt spray exposure, Salt-away, Eastwood, and water washings maintain this high level of corrosion protection; while, Neutro-wash and water and soap only show intermediate levels of corrosion protection. Calculated values of pore resistance can be found in Table 4-6. Values of pore resistance above 10^{10} Ohm cm^2 are considered to be an indication of good coating quality; while pore resistances on the order of 10^7 Ohm cm^2 are considered an indication of intermediate coating quality. Notice that, compared to the coating before salt spray exposure, Salt-away washes increase the pore resistance and therefore improves corrosion protection of the LCC coated metal. These results corroborate visual inspection where Salt-away and Eastwood showed a reduction in creep from the scribe of approximately 30%. Conversely, Water and soap and Neutro-wash show the lowest pore resistance and indicate that the quality of the coating is adversely affected by these wash methods. This breakdown in coating quality could not be seen from visual inspection alone and indicates that the uptake of water into the coating may increase for soap and water and Neutro-wash.

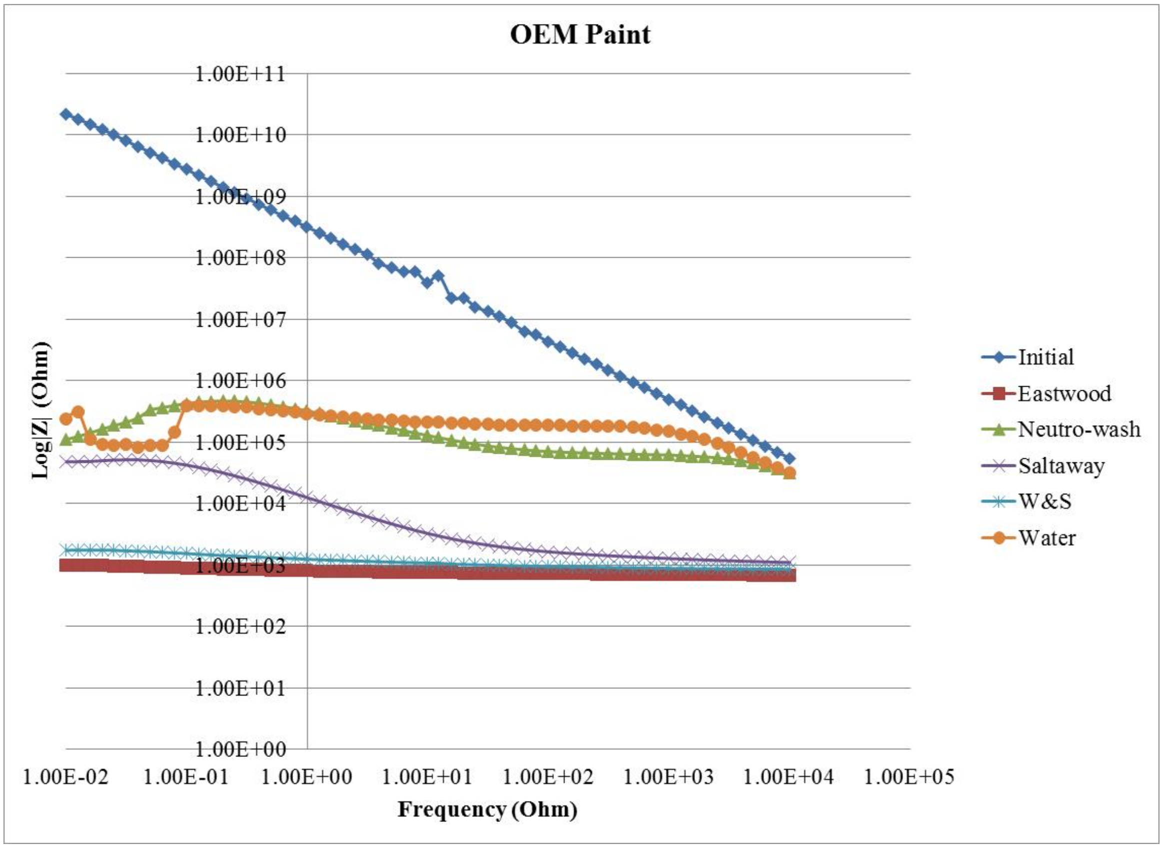


Figure 4-7: Bode plot for LubraSeal on A36 before and after 14 days of salt spray exposure for three salt neutralizers.

EIS analysis for OEM paint coated A36 coupons is shown in Figure 4-7. Referring to Figure 4-2, initially the OEM coating provides a good level of corrosion protection. After 14 days of salt spray exposure, Neutro-wash, Salt-away, and water only wash show moderate levels of corrosion protection; while, Eastwood and soap and water show poor levels of corrosion protection. Calculated values of pore resistance can be found in Table 4-6. Values of pore resistance below 10^5 Ohm cm^2 are considered to be an indication of poor coating quality as well as the uptake of large amounts of water into the coating layer. Notice that all of the salt neutralizers tested on OEM paint coated A36 show poor coating quality after salt spray testing; however, Salt-away and water only show the highest pore resistance. For OEM paint coated samples, the decrease in pore resistance is due to the increased number of blisters and defects on the coating surface. These results contradict visual inspection that show that Eastwood and soap and water have the highest coating rating of the OEM paint coated coupons and indicate that there is an increased amount of coating breakdown occurring at the metal surface that cannot be seen through visual inspection alone.

Table 4-6: Summary of Pore Resistance for Tested Coatings Before and After 14 Days of Salt Spray Exposure

	Pore Resistance (Ohm cm^2)		
	LubraSeal	**LCC**	**OEM Paint**
Initial Coating	2.02×10^5	8.93×10^8	7.41×10^8
Eastwood	2.81×10^2	3.44×10^8	3.52×10^2
Neutro-wash	2.87×10^5	7.50×10^5	2.03×10^3
Salt-away	7.86×10^4	4.70×10^{10}	2.78×10^4
Water and Soap	1.65×10^2	1.10×10^6	9.86×10^2
Water	1.70×10^2	1.33×10^8	6.26×10^5

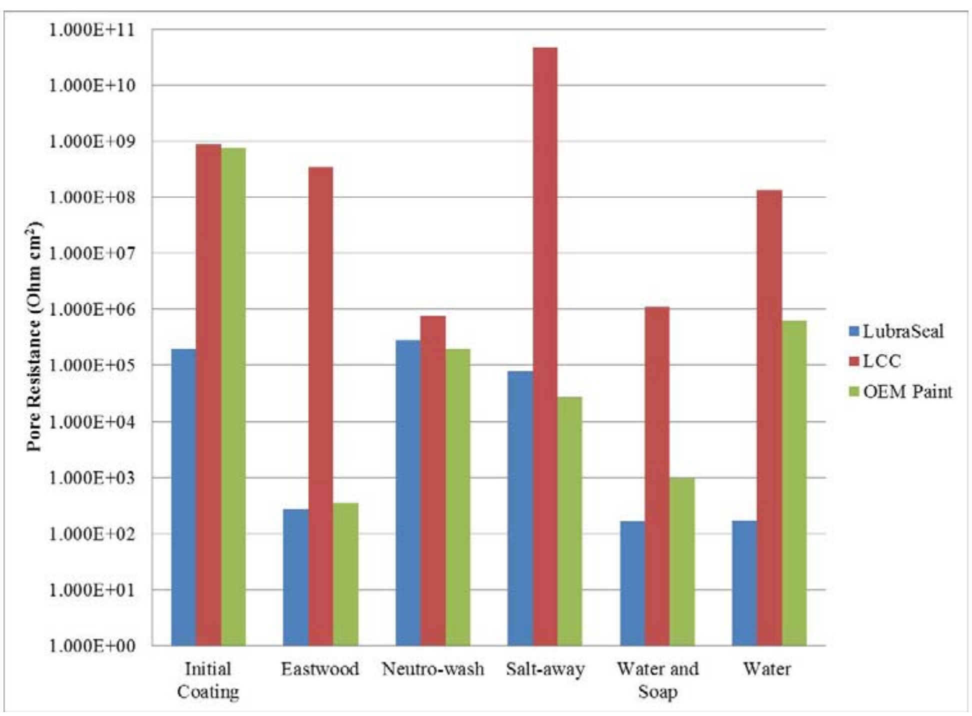
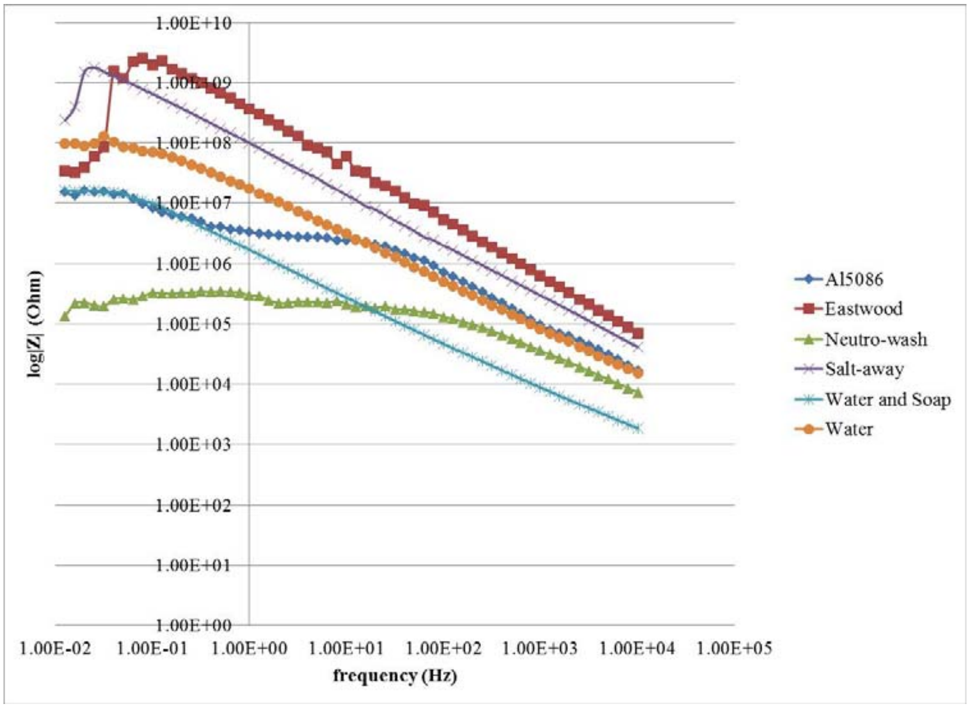
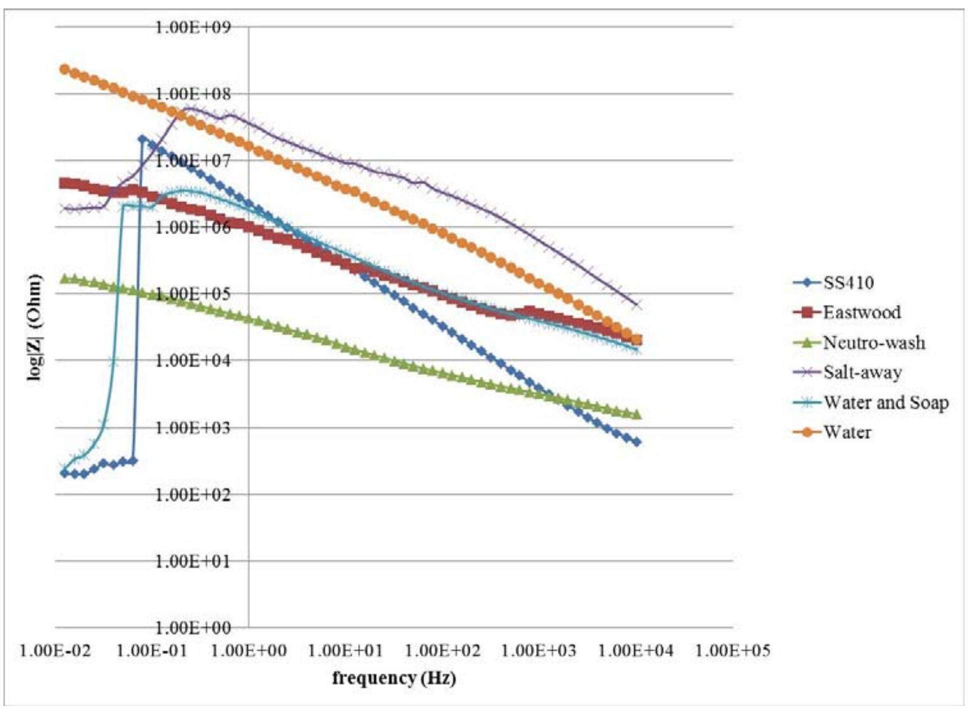


Figure 4-8: Pore resistance (Ohm cm^2) for various wash methods after 14 days of salt spray exposure for three coatings on A36.


1.00E+10
1.00E+09
1.00E+08
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
log|Z| (Ohm)
1.00E-02
1.00E-01
1.00E+00
1.00E+01
1.00E+02
1.00E+03
1.00E+04
1.00E+05
frequency (Hz)
Al5086
Eastwood
Neutro-wash
Salt-away
Water and Soap
Water


1.00E+09
1.00E+08
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
log|Z| (Ohm)
1.00E-02
1.00E-01
1.00E+00
1.00E+01
1.00E+02
1.00E+03
1.00E+04
1.00E+05
frequency (Hz)
SS410
Eastwood
Neutro-wash
Salt-away
Water and Soap
Water

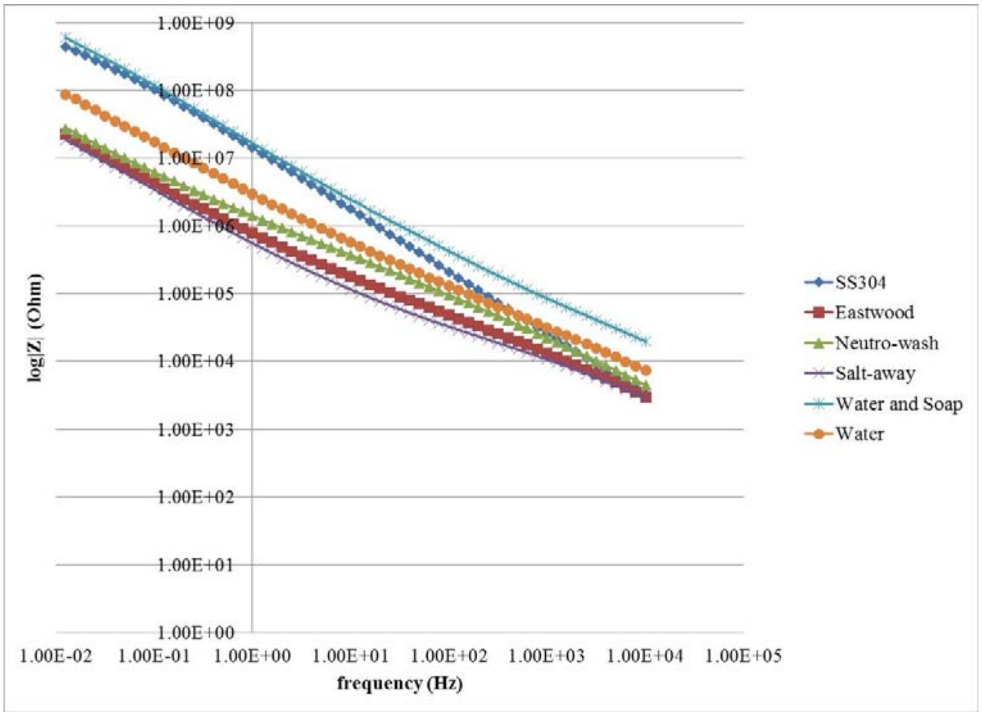
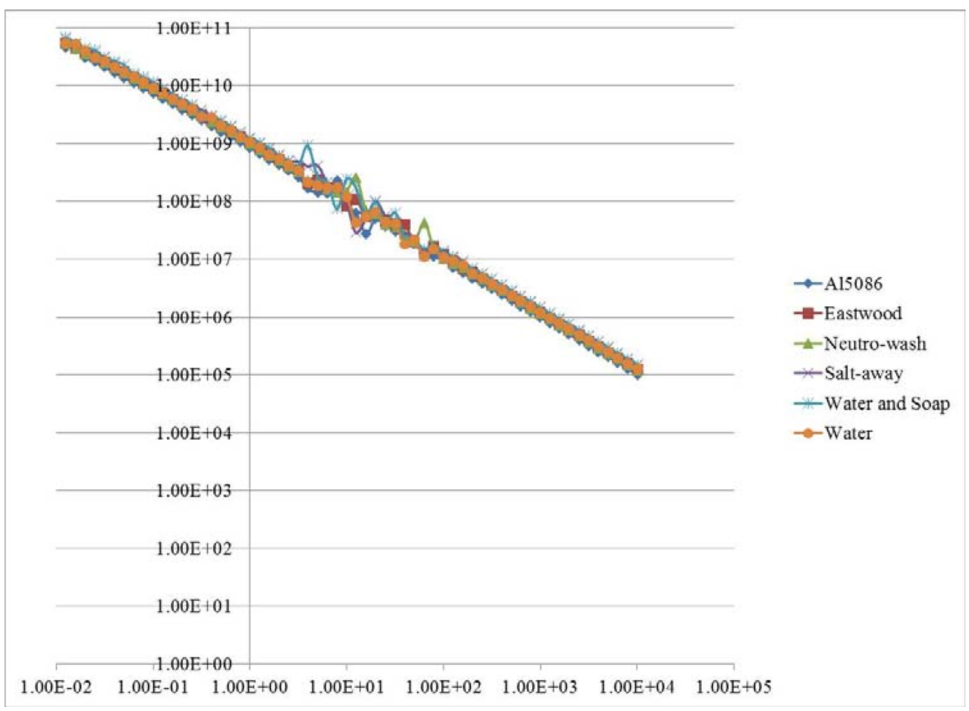
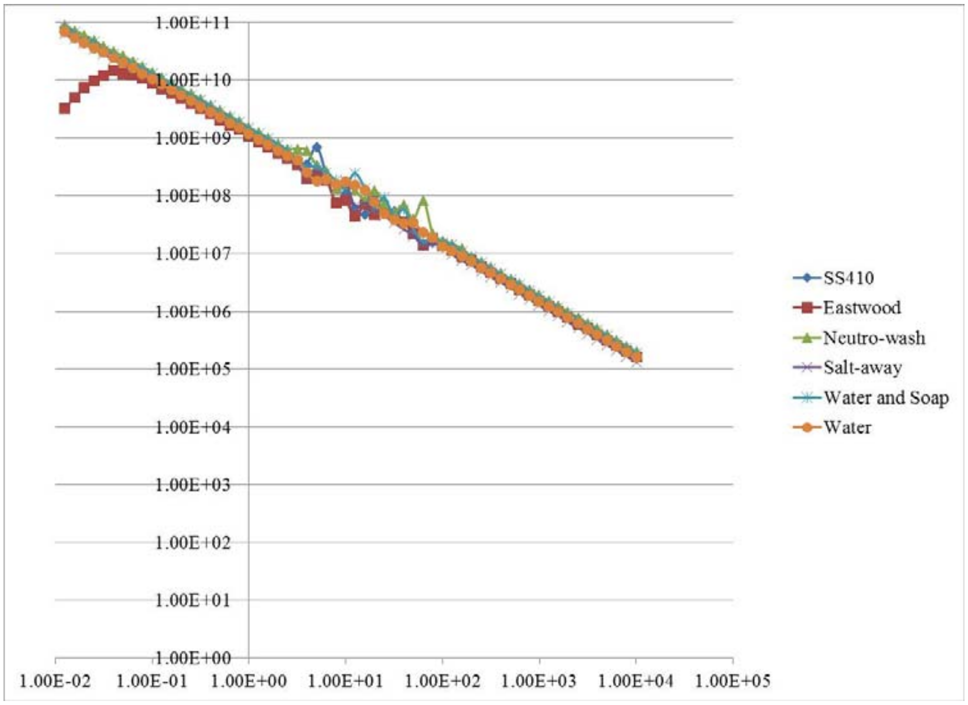


Figure 4-9: EIS data for LubraSeal on Aluminum 5086 (top), 410 Stainless Steel (middle), and 304L Stainless Steel (bottom).





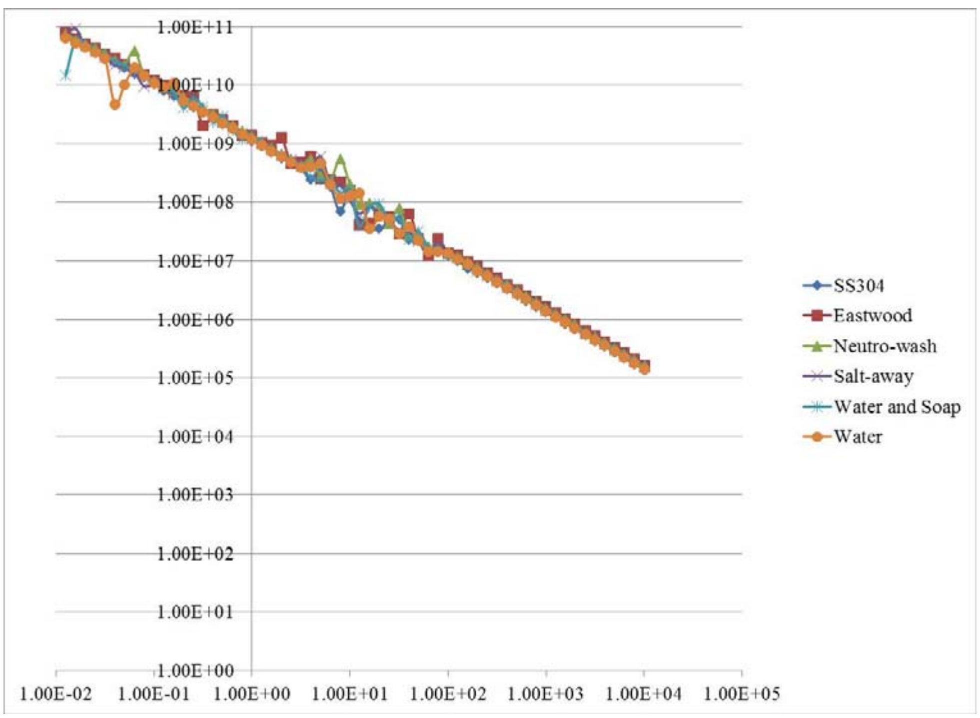


Figure 4-10: EIS data for LCC on Aluminum 5086 (top), 410 Stainless Steel (middle), and 304L Stainless Steel (bottom) before and after 14 days of salt spray exposure.

Figure 4-9 and Figure 4-10 show EIS data for LubraSeal and LCC, respectively. Referring to Figure 4-2, LubraSeal on aluminum and stainless steel maintains good to intermediate coating performance after 14 days exposure to salt spray; while, LubraSeal on carbon steel showed poor coating performance. LCC on aluminum and stainless maintains good coating performance after 14 days of salt exposure, regardless of salt neutralizer application.

4.4. Overview of Effectiveness of Salt Neutralizers at Reducing Corrosion on Coated Metals

- Three coatings on metal coupons were evaluated: OEM paint, LCC, and LubraSeal
- The ability of coatings to prevent corrosion on coated samples is alloy and wash specific. Coated aluminum and stainless steel alloys did not exhibit corrosion while coated carbon steel samples were highly corroded for LubraSeal and highly blistered for OEM paint. LCC on coated samples inhibited corrosion.
- All carbon steel scribed samples without neutralizer application exhibited corrosion.
- Statistically, neutralizer application did not inhibit corrosion on the majority of carbon steel scribed samples. However, the average creep rates for Salt-away and Eastwood were better than soap and water on LCC coated metal coupons.
- These results were corroborated with EIS testing that indicates that Salt-away and Eastwood increase corrosion protection on carbon steel samples coated with LCC.
- EIS tested was used to validate visual inspection. Testing indicated that although some coatings did not appear corroded or blistered during visual inspection, there was indeed a breakdown in corrosion protection occurring at the metal surface. For example, OEM painted samples showed a decrease in coating performance after salt spray testing, even with neutralizer application. LCC coatings, however, maintained coating performance.

CHAPTER V

COST-BENEFIT ANALYSIS OF CORROSION PREVENTION STRATEGIES

5.1. Introduction

The final component in the detailed analysis of corrosion prevention strategies was to conduct a cost analysis. Each of the salt neutralizers identified in Table 2-1 was included in the cost analysis.

5.2. Annual Cash Flow Analysis Approach and Example

Since the laboratory results from the coatings evaluation was primarily qualitative, a cost analysis was only performed on neutralizer solution application. Table 5-1 summarizes the basic cost factors for salt neutralizer application

Table 5-1: Neutralizer Solution Application Cost Factors.

Cost Factor	Units	Description
1. Neutralizer solution	$/gallon	Concentrated solution
2. Dilution ratio	%	Volume dilution percentage (neutralizer solution/total mixed volume)
3. Neutralizer volume used per wash event	gallons	Volume of actual water and neutralizer applied to truck
4. Number of trucks at facility	trucks	Trucks washed with neutralizer

The cost analysis was carried out as an annual cash flow analysis. Annual cash flow analysis is a cost analysis technique that converts costs and/or benefits to a series of uniform annual payments over the expected life of the project, accounting for the time value of money. The equivalent uniform annual cost (EUAC) can be useful when assessing costs as part of an annual operating budget.

Equation 5-1: Neutralizer cost per truck per wash event (NCWE).

$$Neutralizer\ cost\ per\ truck\ per\ wash\ event = \$XX/gallon * XX\ dilution\ ratio\ (as\ a\ decimal) * \frac{XX\ gallons}{1\ wash}$$

So for Salt-Away at $16.15 per gallon, 10% dilution ratio, and 100 gallon wash of diluted neutralizer solution, the cost would be $161.50. Equation 5-2 can then be used to calculate the total cost to a facility as a function of wash events and number of trucks.

Equation 5-2: Neutralizer cost per facility per winter season (NCWS).

$$NCWS = NCWE * Trucks\ at\ facility * Total\ \#\ of\ wash\ events$$

For example, for Salt-Away with an NCWE=$161.50, a facility with 12 trucks and washing the trucks 10 times over the winter season, the NCWS would be $19,380.

In order to assess the potential benefit of reducing the corrosion rate on the winter maintenance trucks and extending the useful life of the truck, the equivalent uniform annual cost (EUAC) must first be calculated (Equation 5-3).

Equation 5-3: Calculation of Equivalent Uniform Annual Costs (EUAC).

$$Annualized\ Capital\ Costs = Capital\ Costs * \left[\frac{i}{((1+i)^n) - 1}\right] + i$$

where:

i = discount rate

n = number of years

For the purposes of this analysis, a discount rate of 7% was used (Veneziano, 2010). The value for n is governed by the truck replacement cycle (8, 10, or 12 years) being assessed. For example, if the capital cost of a tandem truck is $140,000 (ODOT personal communication), a discount rate of 7% is applied, and a replacement cycle of 10 years is input, the EUAC = $19,932.85.

Strictly looking at extending the useful life of the truck as a benefit, the EUAC for a single truck can be used as an estimate of the benefit for applying salt neutralizer solutions to reduce the corrosion rate. For example, if the neutralizer solutions can extend the life of the truck by 1 year (10% of a 10 year replacement cycle), then spending approximately $19,932.85 for neutralizer solution over 10 years would be a net cost-benefit of zero (spending less than this amount on neutralizer solution would result in a net benefit). Additional benefits would also likely include less maintenance labor costs associated with wiring connections.

5.3. Annual Cash Flow Analysis – Neutralizer Comparison and Wash Cycle Determination

Table 5-2 summarizes the solution cost for concentrated solution, tested dilution ratio (per manufacturer recommended ratio range), and usable solution cost. As was noted earlier in the report, but summarized again here in Table 5-3, these dilution ratios often increased the corrosion rate. Therefore, the usable solution cost for dilution ratios that prevented corrosion on stainless steel are summarized in Table 5-4.

Table 5-2: Neutralizer solution cost for concentrated solution, tested dilution ratio (per manufacturer recommended ratio range), and usable solution cost.

Neutralizer	Conc. Solution Cost ($/gallon)	Tested Dilution Ratio (Volume %)	Usable Solution Cost ($/gallon)
Salt-Away	$16.15	10.00	$1.62
BioKleen	$17.50	3.22	$0.56
Neutro-Wash	$36.95	11.00	$4.06
ConSALT	$19.00	10.00	$1.90
Winter Rinse	$30.00	4.50	$1.35
Eastwood	$30.00	4.50	$1.35

Note: Concentrated solution cost based on 55 gallon purchase and includes shipping.

Table 5-3: Qualitative results of accelerated corrosion testing for six commercially available salt neutralizers on bare metal samples at neutralizer manufacturer recommended dilution (see Table 2-1 for details). Conditions that lowered (i.e. "reduces" corrosion) the corrosion rate compared to soap and water are shaded.

	BioKleen	**ConSALT**	**Eastwood**	**Neutro-Wash**	**Salt-Away**	**Winter Rinse**
Carbon Steel (A36)	Increases	Increases	Increases	Increases	Reduces	Increases
Copper	Increases	Increases	Increases	Reduces	Reduces	Increases
Aluminum (2024T3)	Reduces	Increases	Reduces	Reduces	Reduces	Reduces
Brass	No Effect	Increases	Increases	Increases	Reduces	Increases
Stainless Steel (410)	No Effect	No Effect	No Effect	No Effect	No Effect	No Effect
Aluminum (5086)	No Effect	No Effect	No Effect	No Effect	No Effect	No Effect
Stainless Steel (304)	No Effect	No Effect	No Effect	No Effect	No Effect	No Effect

Table 5-4: Neutralizer solution cost for concentrated solution, tested dilution ratio, and usable solution cost for "modified" (i.e. increased dose of neutralizer) application.

Neutralizer	**Conc. Solution Cost ($/gallon)**	**"Modified" Dilution Ratio (Volume %)**	**Usable Solution Cost ($/gallon)**	**A36 Steel Corrosion Rate Reduction (%)**
Salt-Away	$16.15	10.00	$1.62	32%
BioKleen	$17.50	17.00	$2.98	36%
Neutro-Wash	$36.95	14.00	$5.17	14%
ConSALT	$19.00	35.00	$6.65	9%
Winter Rinse	$30.00	10.00	$3.00	9%
Eastwood	$30.00	12.00	$3.60	16%

Note: "Modified" dilution ratio refers to second round of testing to see if increasing the concentration of neutralizer improved the corrosion inhibition ability of the solution. Only Salt-Away dilution ratio remained the same as reported in Table 5-2

Using the costs listed in Table 5-4 and applying the various neutralizer solutions to wash a truck, the cost to thoroughly wash a single truck is significant and can vary by more than 300% depending on the neutralizer product (Figure 5-1). For the two top performing (at "modified" dose to achieve corrosion reduction) neutralizer products (Salt-Away and BioKleen) and Neutro-Wash, the neutralizer cost for a full 350 gallon wash per truck would be $567 for Salt-Away, $1,043 for BioKleen, and $1,810 for Neutro-Wash. If Salt-Away neutralizer is applied at a reduced volume (50 gallons or 100 gallons per truck wash) and neutralizer is applied for five wash events per winter season, the total cost per year to wash the truck is $405 at 50 gallons per wash or $810 at 100 gallons per wash (Figure 5-2).

Finally, assuming replacement cost of ODOT tandem truck is ~$140,000 ($125,000 single axle) and the neutralizer solution can increase the useful life of the truck by 6 months to 1 year, washing the trucks with Salt-Away 5 to 18 times per year (depending on facility location and replacement cycle) is cost-effective (Table 5-5). The benefits could be even greater if the maintenance costs associated with wiring etc. are also reduced and additional truck components (e.g. snow blade) have a longer usable life.

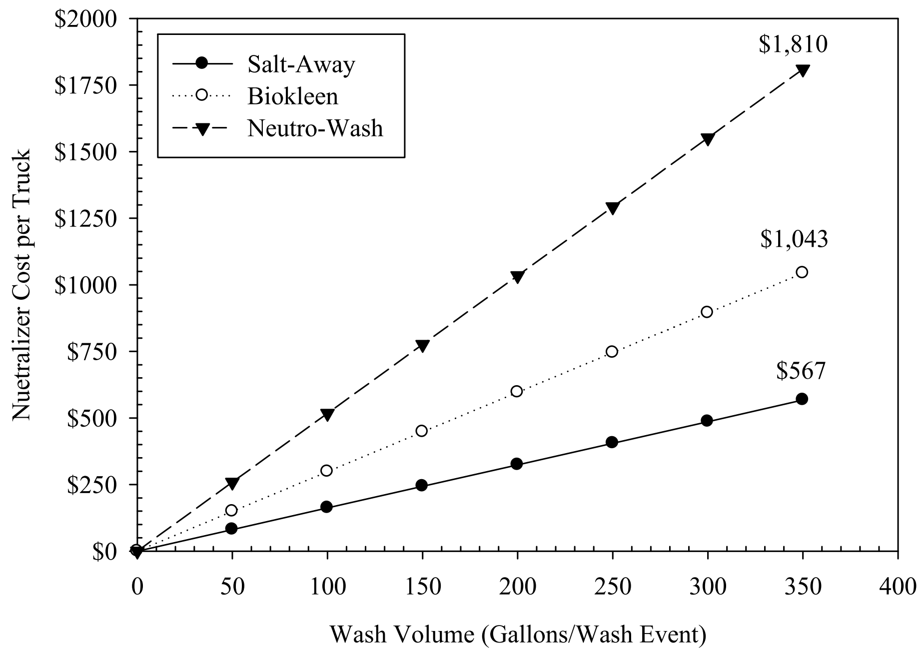


Figure 5-1: Neutralizer cost per truck as a function of neutralizer product and wash volume per wash event. Neutralizer cost per gallon of useable solution (see Table 5-4): Salt-Away ($1.62), BioKleen ($2.98), and Neutro-Wash ($5.17). The neutralizer cost per truck for a wash volume total of 350 gallons is displayed on the figure.

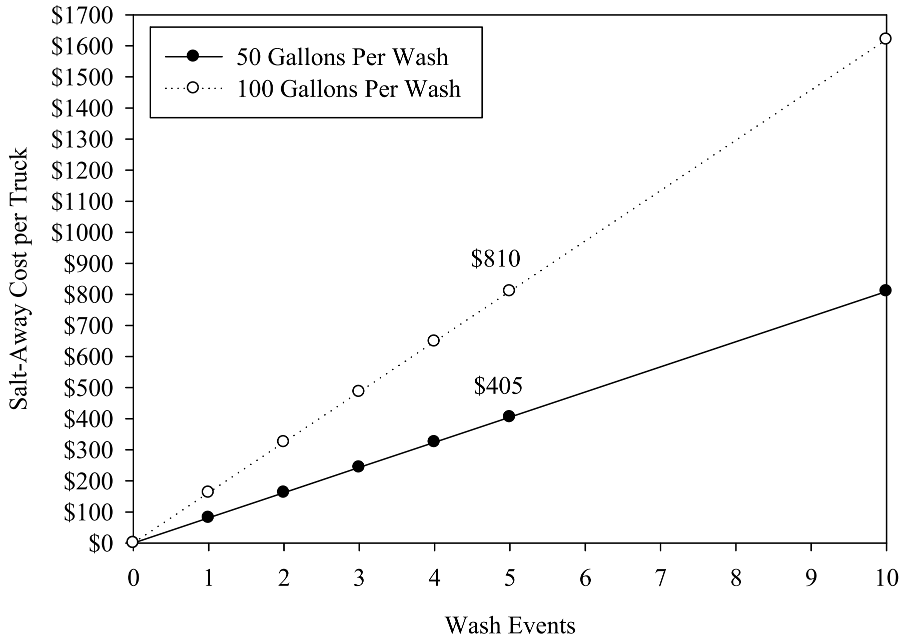


Figure 5-2: Salt-Away cost per truck as a function of wash events and wash volume per wash event. The cost per truck for five wash events is displayed on the figure.

Table 5-5: Cost-benefit analysis (cost-benefit net zero) for estimating the number of 100 gallon Salt-Away usable solution wash events (rounded to whole number) per truck per year as a function of truck replacement cycle useful life extension assumptions.

	Tandem Truck EUAC	**6 Months Extension (# Wash Events)**	**12 Months Extension (# Wash Events)**
8 Years	$23,445.49	9	18
10 Years	$19,932.85	6	12
12 Years	$17,626.28	5	9

Note: Based on tandem truck capital cost $140,000, 7% discount rate, and EUAC is the Equivalent Uniform Annual Cost.

5.4. Overview of Cost-benefit Analysis

- The cost to thoroughly wash a single truck is significant and can vary by more than 300% depending on the neutralizer product (Figure 5-1). For the two top performing (at "modified" dose to achieve corrosion reduction) neutralizer products (Salt-Away and

BioKleen) and Neutro-Wash, the neutralizer cost for a full 350 gallon wash per truck would be $567 for Salt-Away, $1,043 for BioKleen, and $1,810 for Neutro-Wash.

- If Salt-Away neutralizer is applied at a reduced volume (50 gallons or 100 gallons per truck wash) and neutralizer is applied for five wash events per winter season, the total cost per year to wash the truck is $405 at 50 gallons per wash or $810 at 100 gallons per wash (Figure 5-2).
- Assuming replacement cost of ODOT tandem truck is ~$140,000 ($125,000 single axle) and the neutralizer solution can increase the useful life of the truck by 6 months to 1 year, washing the trucks with Salt-Away 5 to 18 times per year (depending on facility location and replacement cycle) is cost-effective (Table 5-5). The benefits could be even greater if the maintenance costs associated with wiring etc. are also reduced.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

This chapter is organized with a section for each results chapter (Chapter 2-Chapter 5), as well as a final section for recommendations for implementation of the research results.

6.1. Overview of Literature and Survey Results

- Literature results on corrosion rates for bare metal surfaces using commercial neutralizer solutions to reduce corrosion on winter maintenance equipment are limited.
- A comprehensive email survey of ODOT districts was conducted to identify current practices for corrosion prevention on snow and ice equipment. Email survey results showed that 37% of respondents use a salt neutralizer. Of these respondents, 100% use Neutro-wash™ as the selected salt neutralizer.

6.2. Overview of Effectiveness of Salt Neutralizers at Reducing Corrosion on Bare Metals

- On all bare metal surfaces tested (seven total) at manufacturer-recommended neutralizer dilution (i.e. gallons of concentrated product per gallon of water), only Salt-Away reduced or had minimal impact on the corrosion rate compared to soap and water (Table 3-1).
- Neutro-Wash had mixed results at manufacturer-recommended neutralizer dilution. Neutro-Wash increased the corrosion rate for carbon steel (A36), copper, and brass but reduced the rate for copper and aluminum (Table 3-1).
- Many of the commercial neutralizer solutions actually increased the rate of corrosion
- (Table 3-1), especially for carbon steel (A36) and copper, two metals of particular concern to ODOT.
- Increasing the neutralizer dose to a value greater than that recommended by the manufacturer made all of the neutralizers effective at reducing the corrosion rate on carbon steel (Figure 3-4). However, this will significantly reduce the cost-effectiveness of

neutralizer application. Salt-Away and BioKleen reduced the corrosion rate by more than 30%.

6.3. Overview of Effectiveness of Salt Neutralizers at Reducing Corrosion on Coated Metals

- Three coatings on metal coupons were evaluated: OEM paint, LCC, and LubraSeal
- The ability of coatings to prevent corrosion on coated samples is alloy and wash specific. Coated aluminum and stainless steel alloys did not exhibit corrosion while coated carbon steel samples were highly corroded for LubraSeal and highly blistered for OEM paint. LCC on coated samples inhibited corrosion.
- All carbon steel scribed samples without neutralizer application exhibited corrosion.
- Statistically, neutralizer application did not inhibit corrosion on the majority of carbon steel scribed samples. However, the average creep rates for Salt-away and Eastwood were better than soap and water on LCC coated metal coupons.
- These results were corroborated with EIS testing that indicates that Salt-away and Eastwood increase corrosion protection on carbon steel samples coated with LCC.
- EIS tested was used to validate visual inspection. Testing indicated that although some coatings did not appear corroded or blistered during visual inspection, there was indeed a breakdown in corrosion protection occurring at the metal surface. For example, OEM painted samples showed a decrease in coating performance after salt spray testing, even with neutralizer application. LCC coatings, however, maintained coating performance.

6.4. Overview of Cost-benefit Analysis

- The cost to thoroughly wash a single truck is significant and can vary by more than 300% depending on the neutralizer product (Figure 5-1). For the two top performing (at "modified" dose to achieve corrosion reduction) neutralizer products (Salt-Away and BioKleen) and Neutro-Wash, the neutralizer cost for a full 350 gallon wash per truck would be $567 for Salt-Away, $1,043 for BioKleen, and $1,810 for Neutro-Wash.
- If Salt-Away neutralizer is applied at a reduced volume (50 gallons or 100 gallons per truck wash) and neutralizer is applied for five wash events per winter season, the total

cost per year to wash the truck is \$405 at 50 gallons per wash or \$810 at 100 gallons per wash (Figure 5-2).

- Assuming replacement cost of ODOT tandem truck is ~\$140,000 (\$125,000 single axle) and the neutralizer solution can increase the useful life of the truck by 6 months to 1 year, washing the trucks with Salt-Away 5 to 18 times per year (depending on facility location and replacement cycle) is cost-effective (Table 5-5). The benefits could be even greater if the maintenance costs associated with wiring etc. are also reduced.

6.5. Recommendations for Implementation

General use of neutralizer products:

1. Overall, Salt-Away™ is the most effective salt neutralizer wash for reducing corrosion of bare metal and coated surfaces. This is based on its performance on all metal surfaces tested and preliminary cost analysis. We recommend Salt-Away as the primary salt neutralizer solution ODOT should implement (contact information provided below).
2. For garages that still have Neutro-Wash or prefer to use Neutro-Wash, the dilution concentration should be increased to at least 14% (volume %) to make it effective at reducing corrosion.
3. For garages using any of the neutralizer solutions listed in Table 3-2, they should use a minimum of the concentration (volume %) reported in Table 3-2.

General use of coatings:

1. Overall, LCC™ is the most effective coating for corrosion protection. This is based on its performance on all metal surfaces tested.
2. For garages that prefer to use LubraSeal, the thickness of the coating should exceed 1 mil.
3. Statistically, neutralizer application did not inhibit corrosion on coated samples. However, the average creep rates for Salt-away and Eastwood were better than soap and water on LCC coated metal coupons.
4. Additional field work is needed on coatings, particularly the long-term durability of the coatings in different environments.

The most cost-effective approach to washing the trucks is to (a) thoroughly rinse them with soap and water first, (b) focus neutralizer solution on targeted areas (i.e. carbon steel), (c) target 100 gallons per wash, and (d) depending on budget and geographic location, wash the trucks 5 to 18 times per year.

Salt-Away Contact
Tom Fultz
Fultz Enterprises, Inc
10509 Kings Way
North Royalton, OH 44133

Ph.: 440-237-9277
FAX: 440-237-9277
Cell: 330-503-2615
email: fultzenterprises@sbcglobal.net
WEB: www.fultz-enterprises.com

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APPENDIX A

SURVEY RESULTS

Table A- 1: Raw data for response to Question 1 from salt neutralizer survey

Please enter the following contact information (we may follow up with additional questions):		
Answer Options	**Response Percent**	**Response Count**
Name:	100.0%	52
District	100.0%	52
Garage-Outpost Name	100.0%	52
Email Address:	98.1%	51
Phone Number:	100.0%	52
answered question		**52**
skipped question		**1**

Table A- 2: Information for survey respondents

Name:	**District**	**Garage-Outpost Name**	**Email Address:**	**Phone Number:**
Brad Mayes	3	Ashland / Wayne	brad.mayes@dot.state.oh.us	330.410.4766
Don Taylor	ONE	Van Wert	Don.Taylor@dot.state.oh.us	419-238-5424
Jason Hoschak	1	Allen County	jason.hoschak@dot.state.oh.us	(419) 999-6711
Mark Drerup	district 01	Hancock County	Mark.Drerup@dot.state.oh.us	419.999.6731
Sandra Knott	Distrist 1	Hardin County	Sandy.Knott@dot.state.oh.us	(419) 999-6741
John A. Borsick	3	Huron County	john.borsick.dot.state.oh.us	(419)744-2243
John A. Borsick	3	Erie County	john.borsick@dot.state.oh.us	(419)499-2351
Roger Peiffer	1	Wyandot County/ Carey Outpost	Roger.Peiffer@dot.state.oh.us	419-294-2383
Tim Maag	District 1	Putnam County Garage	tim.maag@dot.state.oh.us	419-999-6761
Patrick Dille	1	Defiance	patrick.dille@dot.state.oh.us	419-999-

		County		6721
Matthew	3	Medina County / Burbank Outpost	matt.simon@dot.state.oh.us	1-419-207-2881
Gary Langdon	8	Warren County Garage	gary.langdon@dot.state.oh.us	513-933-6740
mark parsley	8	Butler County Garage	mark.parsley@dot.state.oh.us	513-9336728
Josh Wallace	8	Greene County Garage	Josh.Wallace@dot.state.oh.us	513-933-6160
Phil Valentine	5	Licking and Muskingum Counties	phil.valentine@dot.state.oh.us	740-323-5230
Jim Wells	10	Monroe Co		1-740-568-4370
David W. Walton	9	Jackson	dwalton@dot.state.oh.us	740 286 2504
violet courtney	2	680 wood	violet.courtney@dot.state.oh.us	419-353-0866
Mitch Blackford	6	Westerville - Franklin County	mitch.blackford@dot.state.oh.us	614-387-2522
Jeff Whetstone	7	Darke/Mercer Garage	jeffrey.whetstone@dot.state.oh.us	937-497-6864
Rob Latham	5	Coshocton	robert.latham@dot.state.oh.us	740-622-2741
Bob Lenser	7	Montgomery County	robert.lenser@dot.state.oh.us	937-497-6889
Bill Patrick T.M.1	9	Ironton Garage.	B Patrick @ DOT. State. OH. US	1-740-532-1636
Shawn Anverse	7	Miami CO Troy	Shawn Anverse@dot.state.oh.us	937-497-6826
Chris Moore	5	Knox County	cmoore3@dot.state.oh.us	740-323-5279
Craig	9	Brown County Whiteoak Outpost	craig.stout@dot.state.oh.us	937 378-6709
Mark Atkinson	5	Guernsey	Mark.Atkinson@dot.state.oh.us	740-323-5331
Mark Kirkhart	10	Gallia	mark.kirkhart@dot.state.oh.us	740 418-4331

Douglas Riffle	District 5	Fairfield County	douglas.riffle@dot.state.oh.us	740-323-5321
Bruce Mayes	6	Marion	Bruce.Mayes@dot.state.oh.us	740-833-8125
Bill Young	Dist. 6	Mt Gilead & Chesterville Outpost	william.young@dot.state.oh.us	740-833-8135.
Daniel Nartker	9	Highland County	Daniel.Nartker@dot.state.oh.us	740-774-9017
John Tansey	2	Lucas County & Northwood Outpost	john.tansey@dot.state.oh.us	419-373-7046
Chris Niziol	9	Lucasville-Wheelersburg	Christopher.Niziol@dot.state.oh.us	(740)-259-2071
Lee Anderson	Two	Williams County Garage	lee.anderson@dot.state.oh.us	419-485-3505
Richard Shatzer	2	Fulton County	richard.shatzer@dot.state.oh.us	419-409-0116
Mike Elliott	6	Fayette Co.	Mike.Elliott@dot.state.oh.us	740 833-8111
Shawn Rostorfer	6	Madison - London Garage	shawn.rostorfer@dot.state.oh.us	740-833-8120
Jack Marshall	6	Union County	jack.marshall@dot.state.oh.us	740-833-8146
Bill Cunningham	Six	Pickaway	William.Cunningham@dot.state.oh.us	740.833.8139
Craig Schneiderbauer	2	Henry County	Craig.Schneiderbauer@dot.state.oh.us	419.373.7025
Patrick Lloyd	9	West Union Garage & Peebles Outpost	patrick.lloyd@dot.state.oh.us	740-774-9001
Bert Tooms	10	Morgan County Garage	bert.tooms@dot.state.oh.us	(740)568-4381
Ron Neuhauser	10	Hocking County	ron.neuhauser@dot.stste.oh.us	740-568-4341
John Burdette	10	Meigs Co. garage	jonh.burdette@dot.state.oh.us	740-568-4351
Shawn Flannery	10	Athens County	Shawn.Flannery@dot.state.oh.us	740-568-4321
Ray Henry	10	Noble	Ray.Henry@dot.state.oh.us	740-568-

		County Garage		4401
Rick Venham	10	Washington County	richard.venham@dot.state.oh.us	740-568-4422
Jamie	10	District	Jamie.Hendershot@dot.state.oh.us	
Ensinger Test	Four	District Office	Paul.Ensinger@dot.state.oh.us	330-786-3135
Brian Olson	4	Dist	brian.olson@dot.state.oh.us	330-786-3112

Table A- 3: Raw data for response to Question 2 from salt neutralizer survey for what deicing chemical and materials are used by each facility

What deicing chemicals and materials are used by your facility (check all that apply)?		
Answer Options	**Response Percent**	**Response Count**
Sodium Chloride (Salt) Brine	98.0%	50
Calcium Magnesium Acetate	2.0%	1
Magnesium Chloride	2.0%	1
Calcium Chloride Liquid	88.2%	45
Calcium Chloride Flakes	5.9%	3
Potassium Acetate	0.0%	0
Sand-Grit	45.1%	23
Carbohydrate or Agricultural Based Solutions (ie; Beat Heat)	17.6%	9
Other (please specify)		3
answered question		**51**
skipped question		**2**

Table A- 4: Raw data for response to Question 3 from salt neutralizer survey regarding use of salt neutralizing solutions to remove salt residue from winter maintenance vehicles.

Does your facility use salt neutralizing solutions to remove salt residue from winter maintenance vehicles?		
Answer Options	**Response Percent**	**Response Count**
Yes	37.7%	20
No	62.3%	33
answered question		**53**
skipped question		**0**

Table A- 5: Raw data for response to Question 4 for what neutralizers are used by ODOT districts. Question 4 was only asked of respondents who answered “yes” to Question 3.

What salt neutralizing product do you use?		
Answer Options	**Response Percent**	**Response Count**
Neutro-wash	100.0%	14
Salt Guard XT	0.0%	0
Winter Rinse	0.0%	0
Eastwood salt neutralizer	0.0%	0
Other (please specify)		5
answered question		**14**
skipped question		**39**

Other (please specify)*
Krown MR 35
Sizzle Truck Wash
salt off
Con-Salt
CONSALT - SALT NEUTRALIZER

*Note: Krown MR 35 and Sizzle Truck Wash are not salt neutralizers and were therefore were not used in this study

Table A- 6: Raw data for response to Question 5 to determine what salt neutralizer application method is used by ODOT districts. Question 5 was only asked of respondents who answered “yes” to Question 3.

What salt neutralizer application method do you use?		
Answer Options	**Response Percent**	**Response Count**
Automated wash system	0.0%	0
Hand washing	55.0%	11
Pressure washing system	65.0%	13
Other (please specify)		2
answered question		**20**
skipped question		**33**

Other (please specify)
Use a garden hose to apply
Undercarriage Wash Unit

Table A- 7: Survey responses to Question 6 regarding what features of their salt neutralizer they like/dislike. Question 6 was only asked of respondents who answered "yes" to Question 3.

What particular features of your salt neutralizer do you like or dislike?	
Answer Options	**Response Count**
	13
answered question	**13**
skipped question	**40**
Response Text:	
Too soon we are just starting to use	
This will be our first year	
It can be sprayed on with pressure washer	
I like the fact that it reduces rust on the equipment	
This will be the first season we have used this item.	
Applied with hand sprayer to radiators. Hopefully prolonging life of radiators. Very hard to measure results because of varibles.	
Removes all salt residue off of equipment after use.	
The neutralizer removes the salt residue and can be run through the brine pumps and systems for storage	
This is the first year we our using this equipment and neutralizer I hope it will reduce rust and parts replacement.	
This will be our first year of using this product.	
We like the product with the little time we have had to use it.	

Table A- 8: Survey responses to Question 7 rating the effectiveness at salt neutralizers at reducing corrosion in the field. Question 7 was only asked of respondents who answered "yes" to Question 3.

How would you rate the effectiveness of the salt neutralizer at reducing corrosion in the field?						
Answer Options	**Very effective**	**Effective**	**Slightly effective**	**Not Sure**	**Rating Average**	**Response Count**
	1	10	3	6	1.50	20
Effectiveness assessment based on?						8
answered question						**20**
skipped question						**33**

Table A- 9: Metrics used by respondents to assess effectiveness of salt neutralizers at reducing corrosion in the field.

Effectiveness assessment based on?
Appearance
Visual Inspections
This will be our first year using this material.
Experience
Not used yet
Slowed down the electronic break downs on the equipment.
Cleanliness of the equipment
based on what I read.

Table A- 10: Survey responses to Question 8. This question was designed to determine if respondents that answered "no" to Question 3 had previously used a salt neutralizer.

Have you used a salt neutralizer in the past?		
Answer Options	**Response Percent**	**Response Count**
Yes	23.5%	8
No	76.5%	26
answered question		**34**
skipped question		**19**

Table A- 11: Survey responses to Question 9. This question was designed to determine why respondents that answered "yes" to Question 8 discontinued use of salt neutralizers.

Why did you stop/discontinue use of the salt neutralizer?		
Answer Options	**Response Percent**	**Response Count**
Cost	80.0%	4
Ineffective	20.0%	1
Time constraints	40.0%	2
Other (please specify)		3
answered question		**5**
skipped question		**48**

Other (please specify)
Because of the acid content. Will use new product MR35 this season.
Lack of use.
I don't know

Table A- 12: Survey responses to Question 10 to determine the prevalence of corrosion protective coatings by ODOT disctricts. This question was asked of all respondents.

Does your facility use corrosion protective coatings (such as LubraSeal)?		
Answer Options	**Response Percent**	**Response Count**
Yes	36.5%	19
No	61.5%	32
Not Sure	1.9%	1
answered question		**52**
skipped question		**1**

Table A- 13: Survey responses to Question 11 to determine what corrosion protective coatings are used ODOT disctricts. Question 11 was only asked of respondents who answered “yes” to Question 10.

What type of corrosion protective coating does your facility use?	
Answer Options	**Response Count**
	18
answered question	**18**
skipped question	**35**
	Response Text
	Krown T 40
	Product from Krown?
	Krown
	This year using a Krown product T-40
	Dura seal
	lube master lube trac plus
	We have used Luberseal in Muskingum County about 3 years ago. Since they have used just an undercoating paint.
	lubra seal
	Rhomar Lubra Seal.
	Lubra seal
	Lubral Seal
	LubraSeal
	LubraSeal
	We have used Lubra seal at the end of winter when we cleaned up equipment for the summer.
	Lubra-seal
	Lubra-Seal
	Rhomar Lubra Seal
	Test.

Table A- 14: Survey responses to Question 12 rating the effectiveness at coatings at reducing corrosion in the field. Question 12 was only asked of respondents who answered "yes" to Question 10.

How would you rate the effectiveness of the protective coating at preventing corrosion?						
Answer Options	**Very effective**	**Effective**	**Slightly effective**	**Not Sure**	**Rating Average**	**Response Count**
	2	9	6	3	1.90	20
Effectiveness assessment based on?						13
answered question						**20**
skipped question						**33**

Table A- 15: Metrics used by respondents to assess effectiveness of coatings at reducing corrosion in the field.

Effectiveness assessment based on?
Appearance
First Time Used This Year
Will know more after this winter season
Experience
Repairs performed based on corrosion
Annual inspection.
The trucks do not deteriorate as fast.
Depending how well protective coating is applied
Two Years Use
Slows down the rust
We still saw rust the next year.
Number of repairs required
Past Experience

Table A- 16: : Raw data for response to Question 13 from salt neutralizer survey regarding use of salt neutralizing solutions in combination with corrosion protective coatings as a corrosion prevention strategy. Question 13 was only asked to those respondents who answered “yes” to Question 10.

Do you use a salt neutralizer on your equipment protected with coatings (such as LubraSeal)?		
Answer Options	**Response Percent**	**Response Count**
Yes	47.6%	10
No	52.4%	11
answered question		**21**
skipped question		**32**

Table A- 17: Survey responses to Question 14 rating the effectiveness of the combination of salt neutralizers and coatings at reducing corrosion in the field. Question 14 was only asked of respondents who answered “yes” to Question 13.

How would you rate the effectiveness of salt neutralizers at preventing corrosion on coated metal?						
Answer Options	**Very effective**	**Effective**	**Slightly effective**	**Not at all effective**	**Rating Average**	**Response Count**
	0	6	3	1	2.50	10
answered question						**10**
skipped question						**43**

Table A- 18: Survey responses to Question 15 allowing respondents to provide additional comments if desired. Question 15 was asked of all participants.

Thanks for your input. Please make any other comments in the box below.	
Answer Options	**Response Count**
	4
answered question	**4**
skipped question	**49**
	Response Text
	As I mentioned we are just starting to use a neutralizer this season.
	Always interested in new products.
	With the start of this new product, there has been been enought time to monitor the results.
	This will be our first year using Neutralizer with undercarrage wash. Used lubra seal on V box spreader chain/belt. Have any questions call.

APPENDIX B

IMAGES FROM ACCELERATED CORROSION TESTING ON SCRIBED COATED METAL SAMPLES

Figure B- 1: Scanned images of scribed metal coupons coated with LCC after 7 days of salt spray exposure. Salt-away was applied every 24 hours.

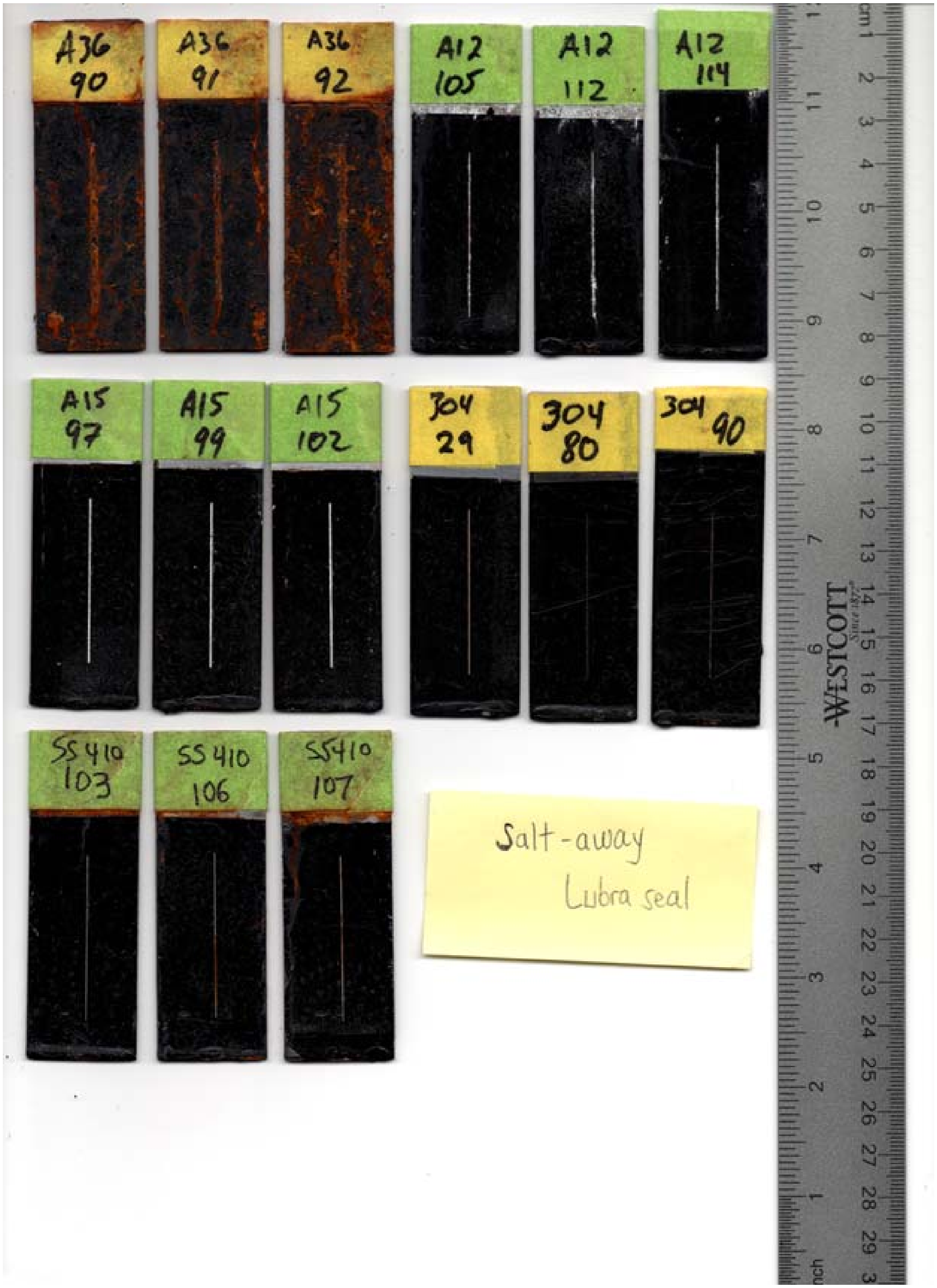

Figure B- 2: Scanned images of scribed metal coupons coated with LubraSeal after 7 days of salt spray exposure. Salt-away was applied every 24 hours.

Figure B- 3: Scanned images of scribed metal coupons coated with LCC after 7 days of salt spray exposure. Neutro-wash was applied every 24 hours.

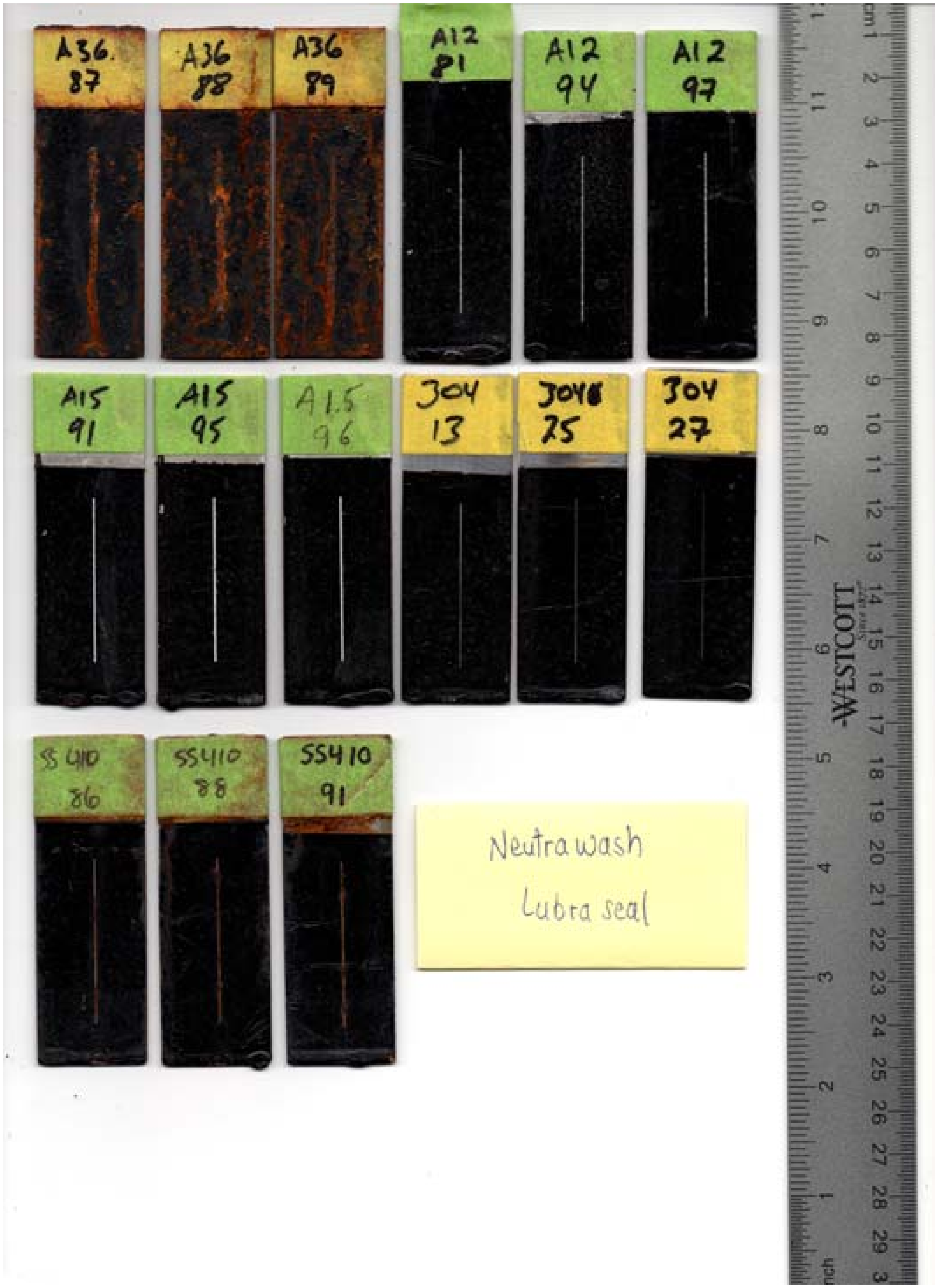

Figure B- 4: Scanned images of scribed metal coupons coated with LubraSeal after 7 days of salt spray exposure. Neutro-wash was applied every 24 hours.

Figure B- 5: Scanned images of scribed metal coupons coated with LCC after 7 days of salt spray exposure. Eastwood was applied every 24 hours.

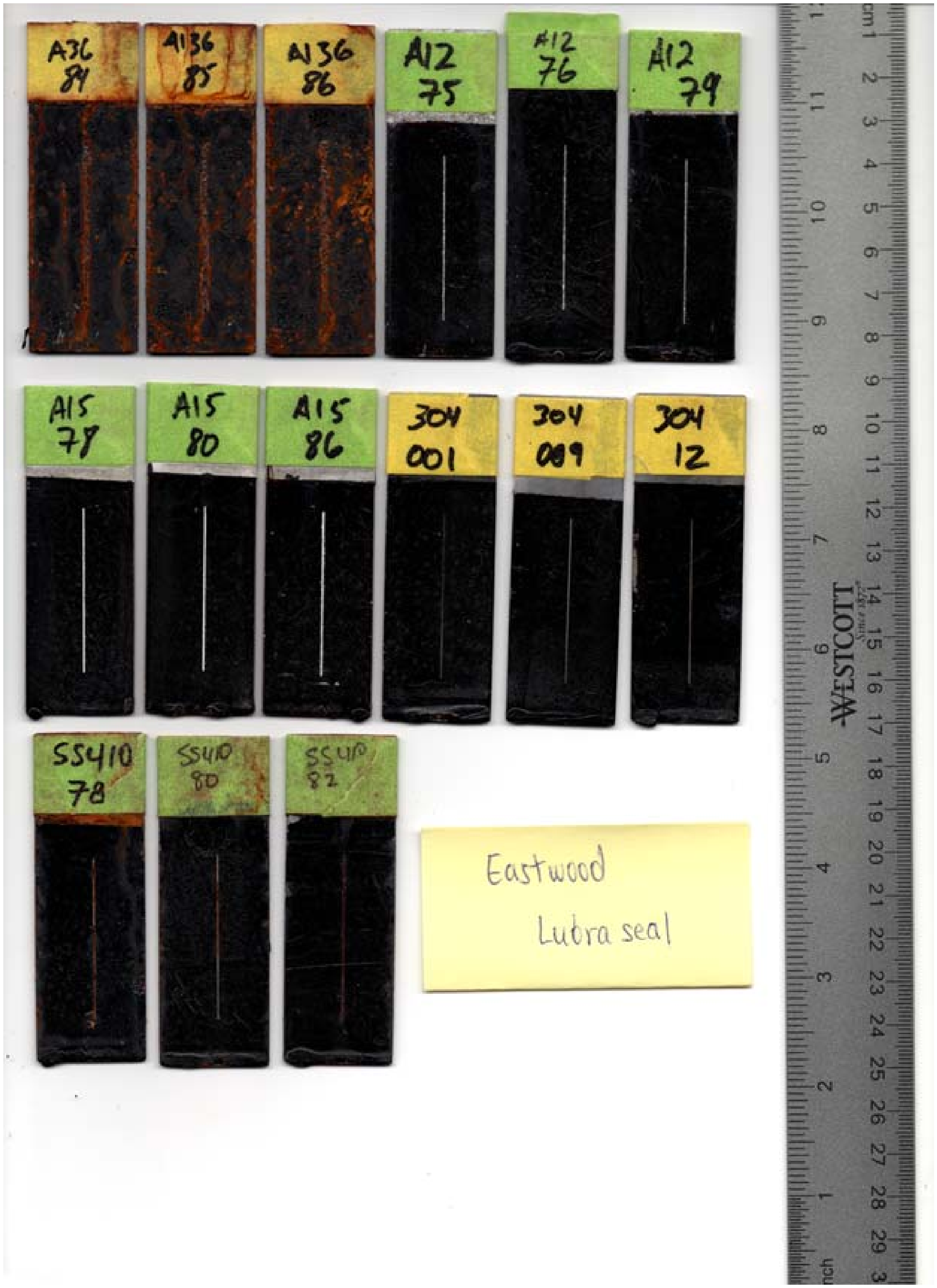

Figure B- 6: Scanned images of scribed metal coupons coated with LubraSeal after 7 days of salt spray exposure. Eastwood was applied every 24 hours.

Figure B- 7: Scanned images of scribed metal coupons coated with LCC after 7 days of salt spray exposure. The coupons were washed with soap and water every 24 hours.

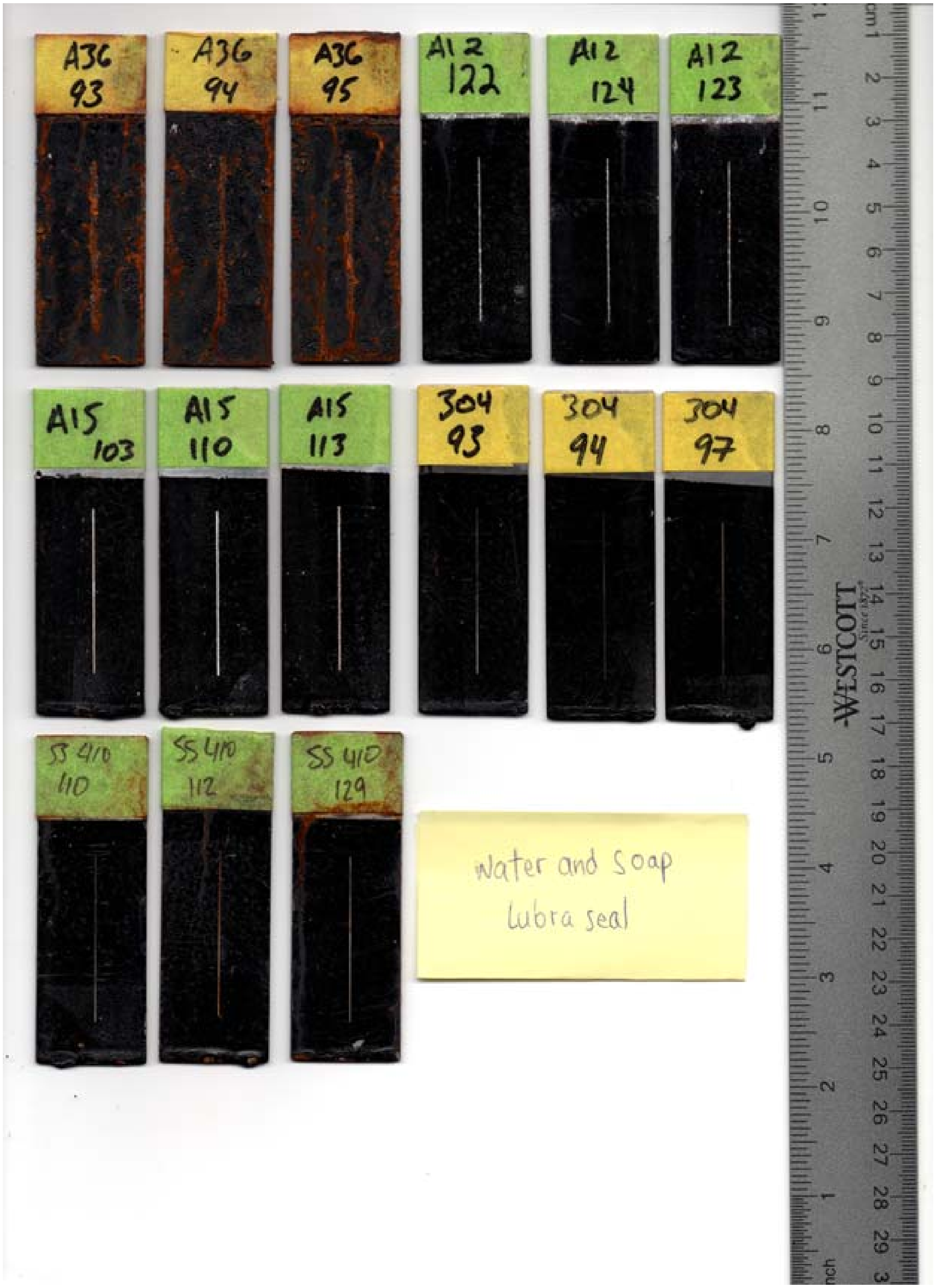

Figure B- 8: Scanned images of scribed metal coupons coated with LubraSeal after 7 days of salt spray exposure. The coupons were washed with soap and water every 24 hours.

Figure B- 9: Scanned images of scribed metal coupons coated with LCC after 7 days of salt spray exposure. The coupons were washed with water every 24 hours.

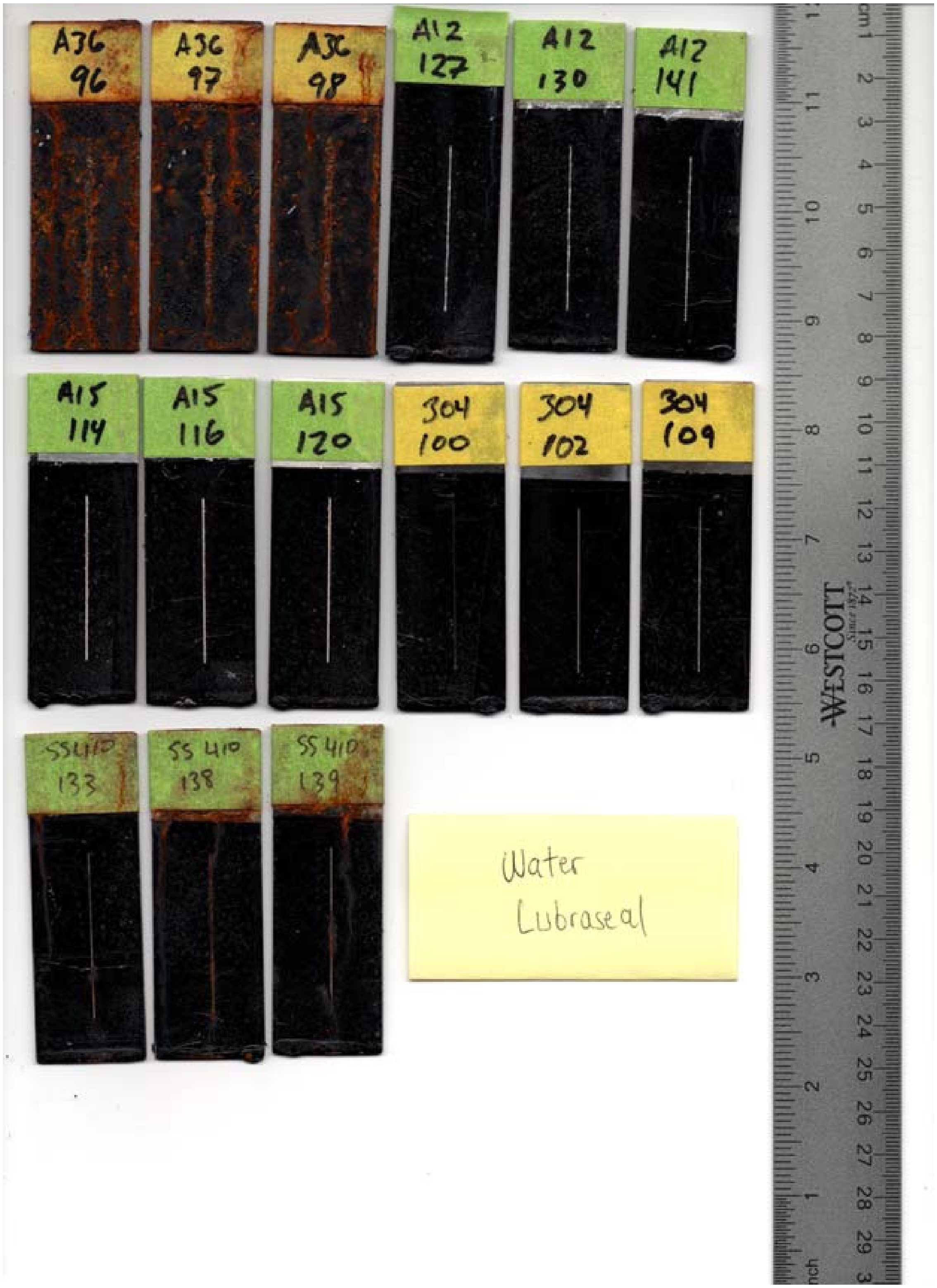

Figure B- 10: Scanned images of scribed metal coupons coated with LubraSeal after 7 days of salt spray exposure. The coupons were washed with water every 24 hours.

Figure B- 11: Scanned images of scribed A36 coupons coated with OEM paint after 7 days of salt spray exposure. The coupons were washed every 24 hours.

APPENDIX C

IMAGES FROM ACCELERATED CORROSION TESTING ON UNSCRIBED COATED METAL SAMPLES

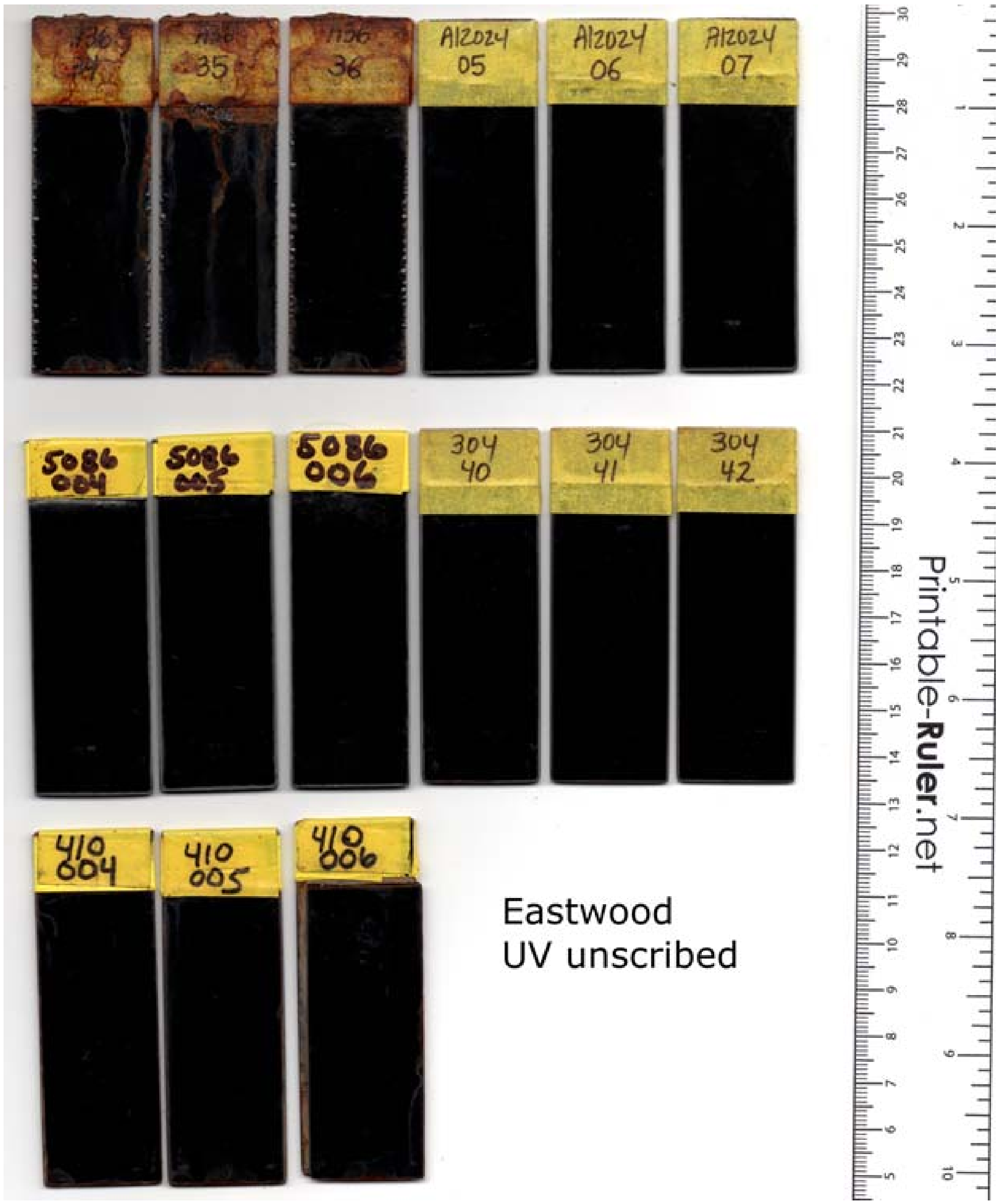

Figure C- 1: Scanned images of metal coupons coated with LCC after 14 days of salt spray exposure. Eastwood was applied every 24 hours.

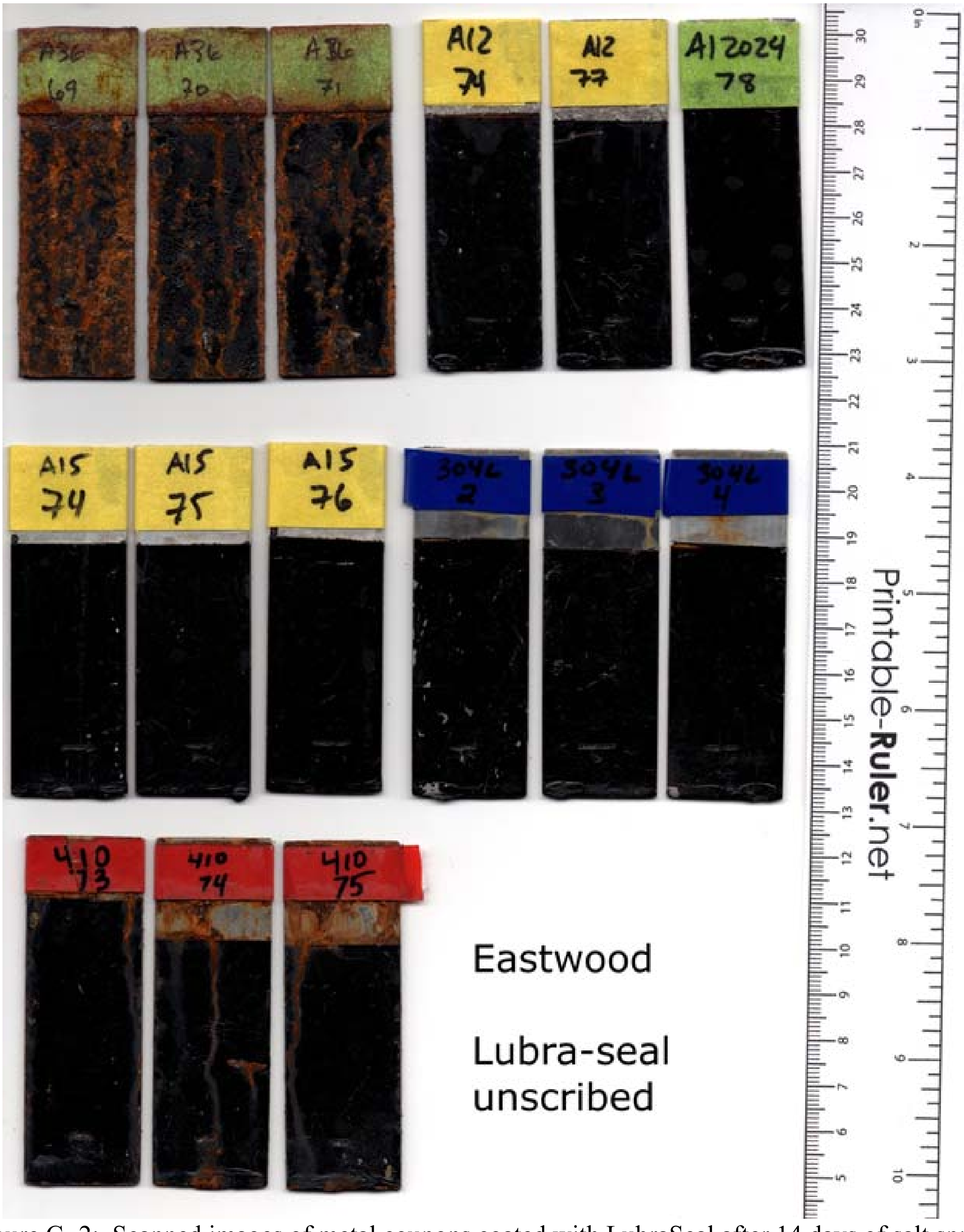

Figure C- 2: Scanned images of metal coupons coated with LubraSeal after 14 days of salt spray exposure. Eastwood was applied every 24 hours.

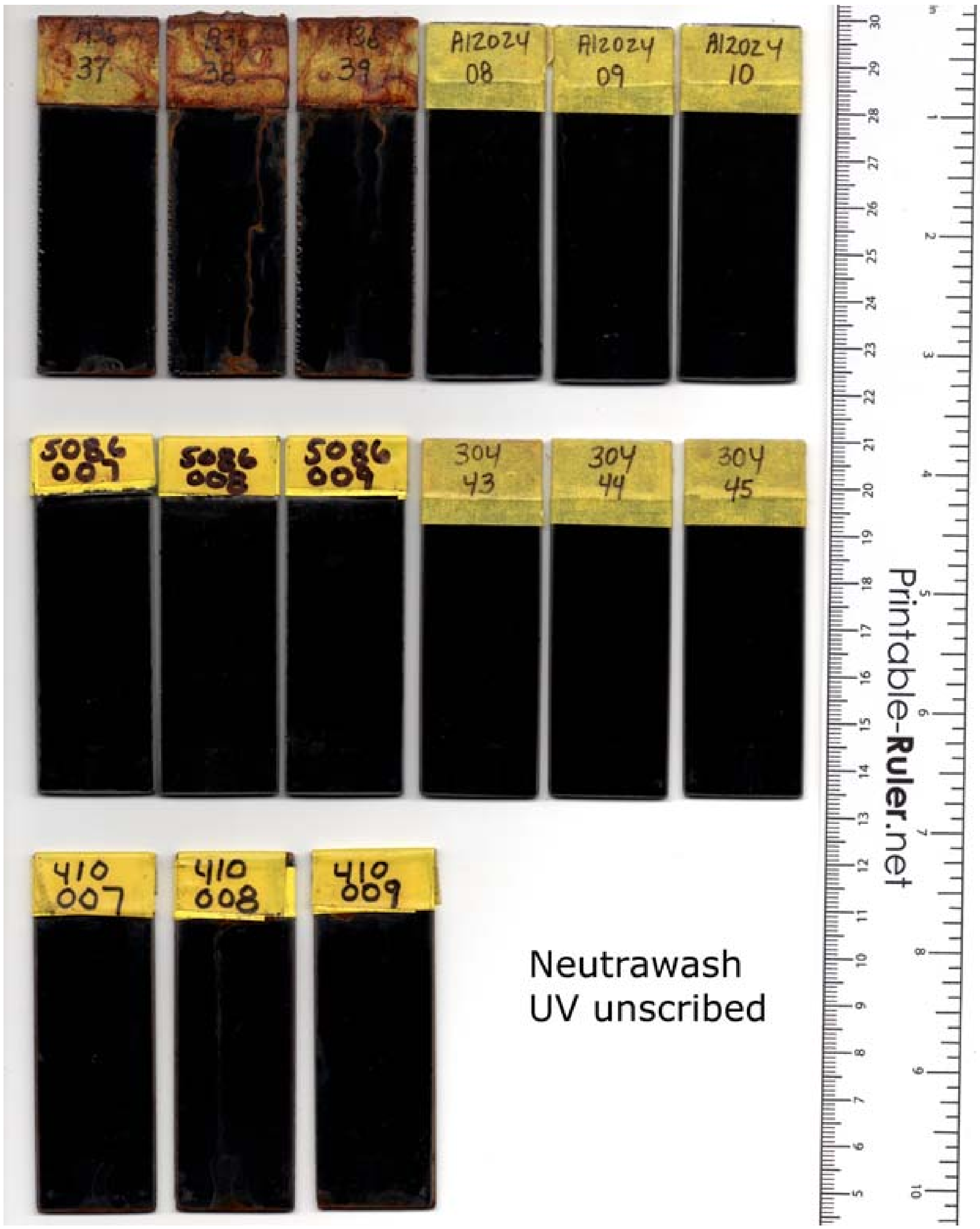

Figure C- 3: Scanned images of metal coupons coated with LCC after 14 days of salt spray exposure. Neutro-wash was applied every 24 hours.

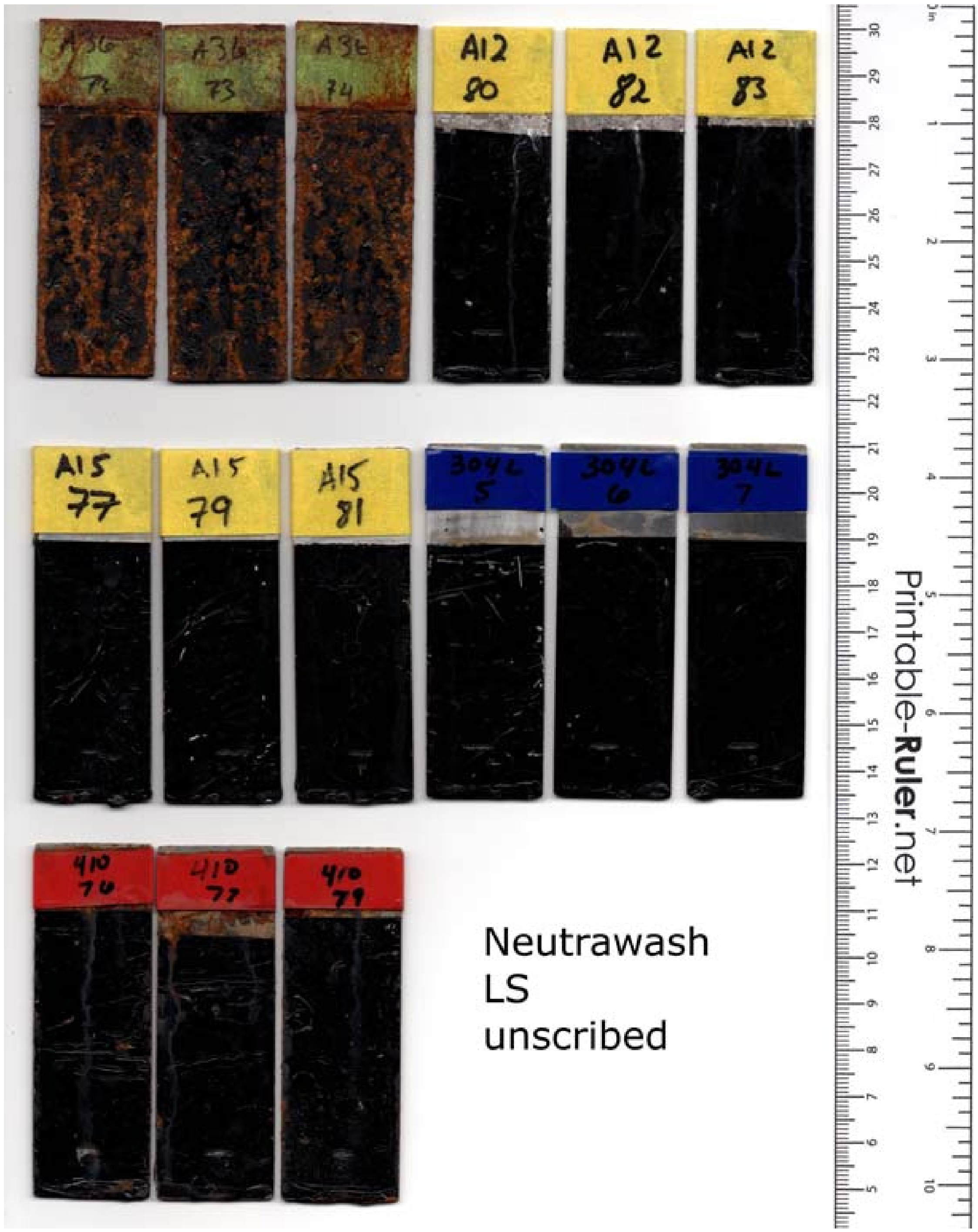

Figure C- 4: Scanned images of metal coupons coated with LubraSeal after 14 days of salt spray exposure. Neutro-wash was applied every 24 hours.

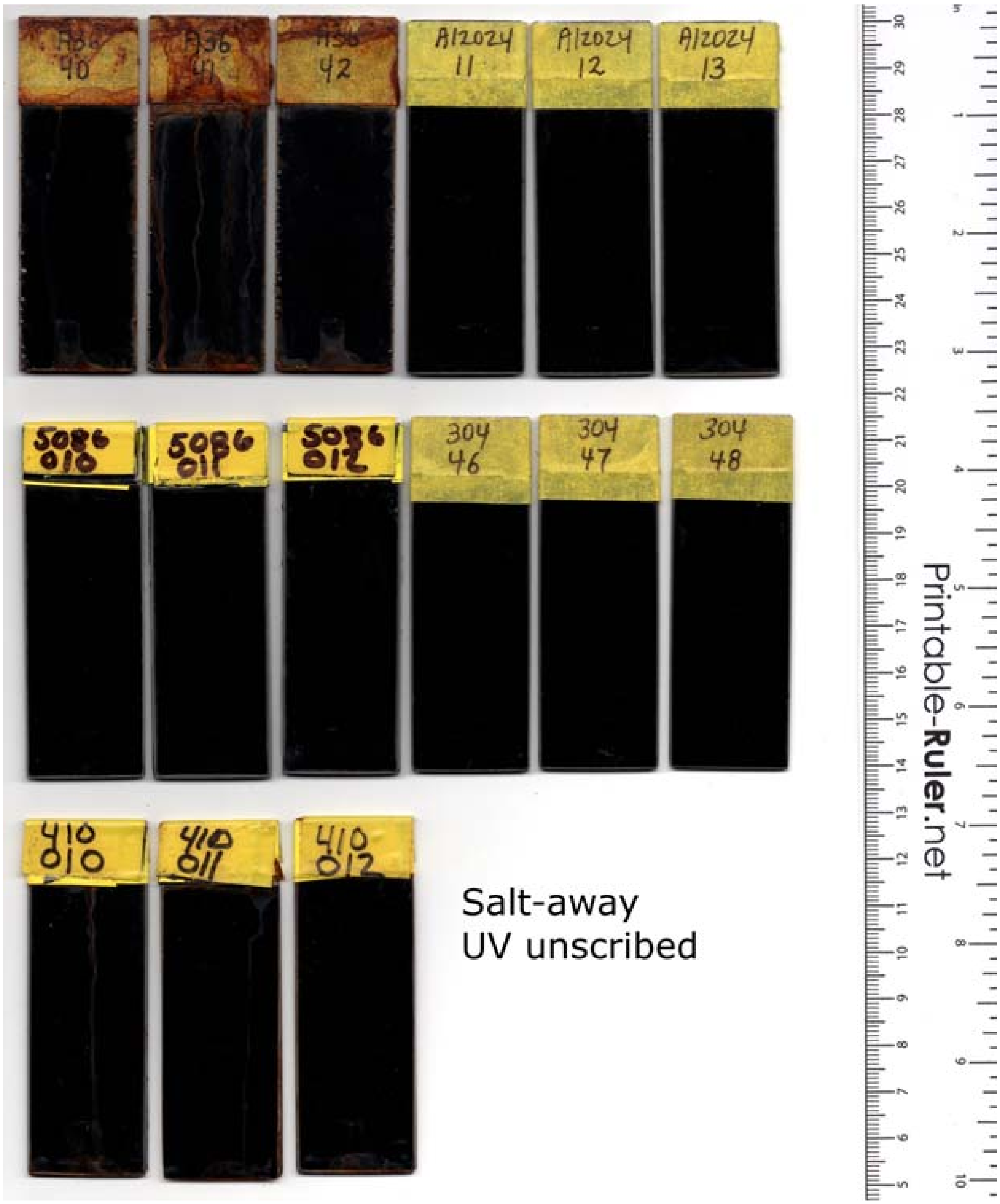

Figure C- 5: Scanned images of metal coupons coated with LCC after 14 days of salt spray exposure. Salt-away was applied every 24 hours.

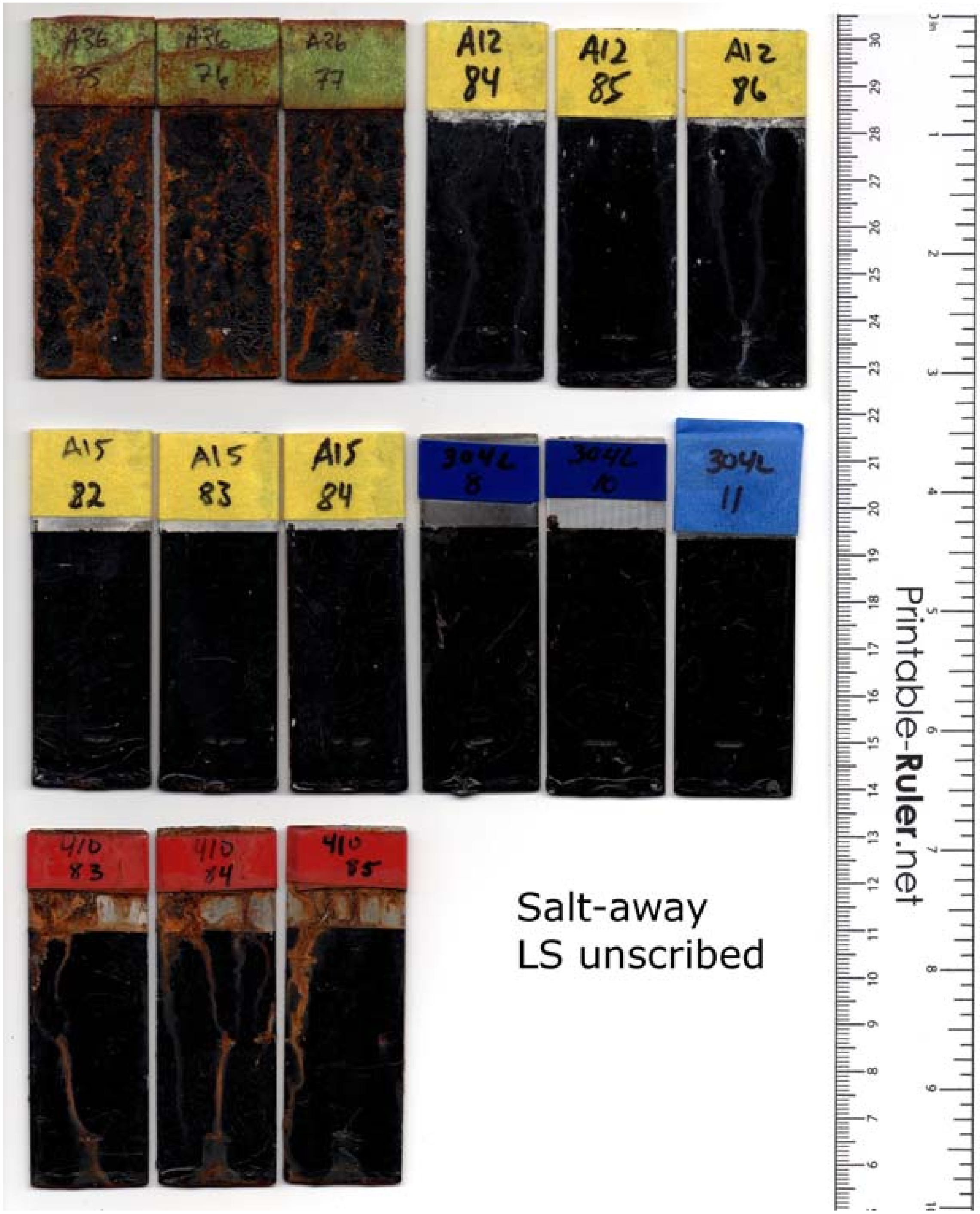

Figure C- 6: Scanned images of metal coupons coated with LubraSeal after 14 days of salt spray exposure. Salt-away was applied every 24 hours.

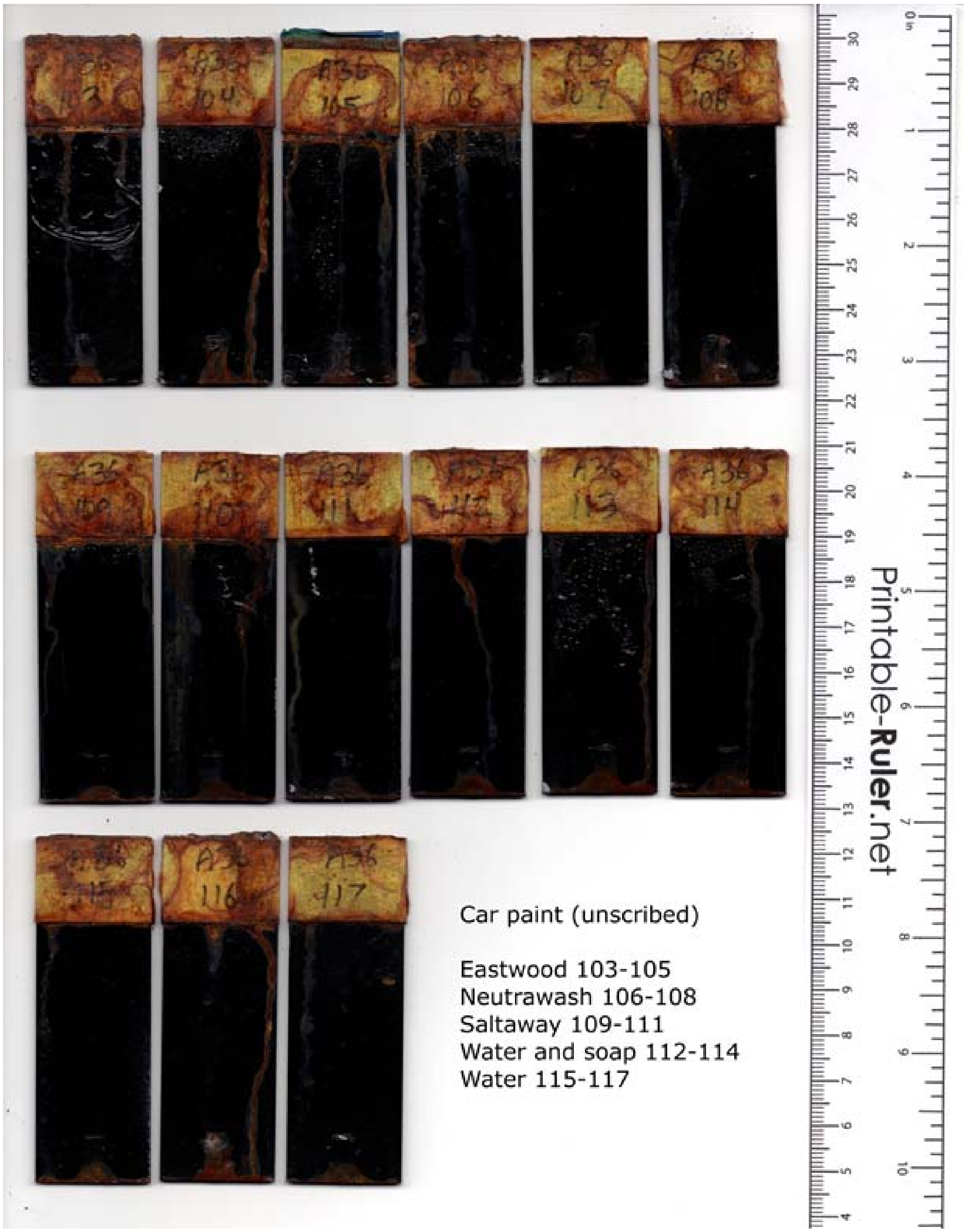

Figure C- 7: Scanned images of A36 coupons coated with OEM paint after 14 days of salt spray exposure. The coupons were washed every 24 hours.

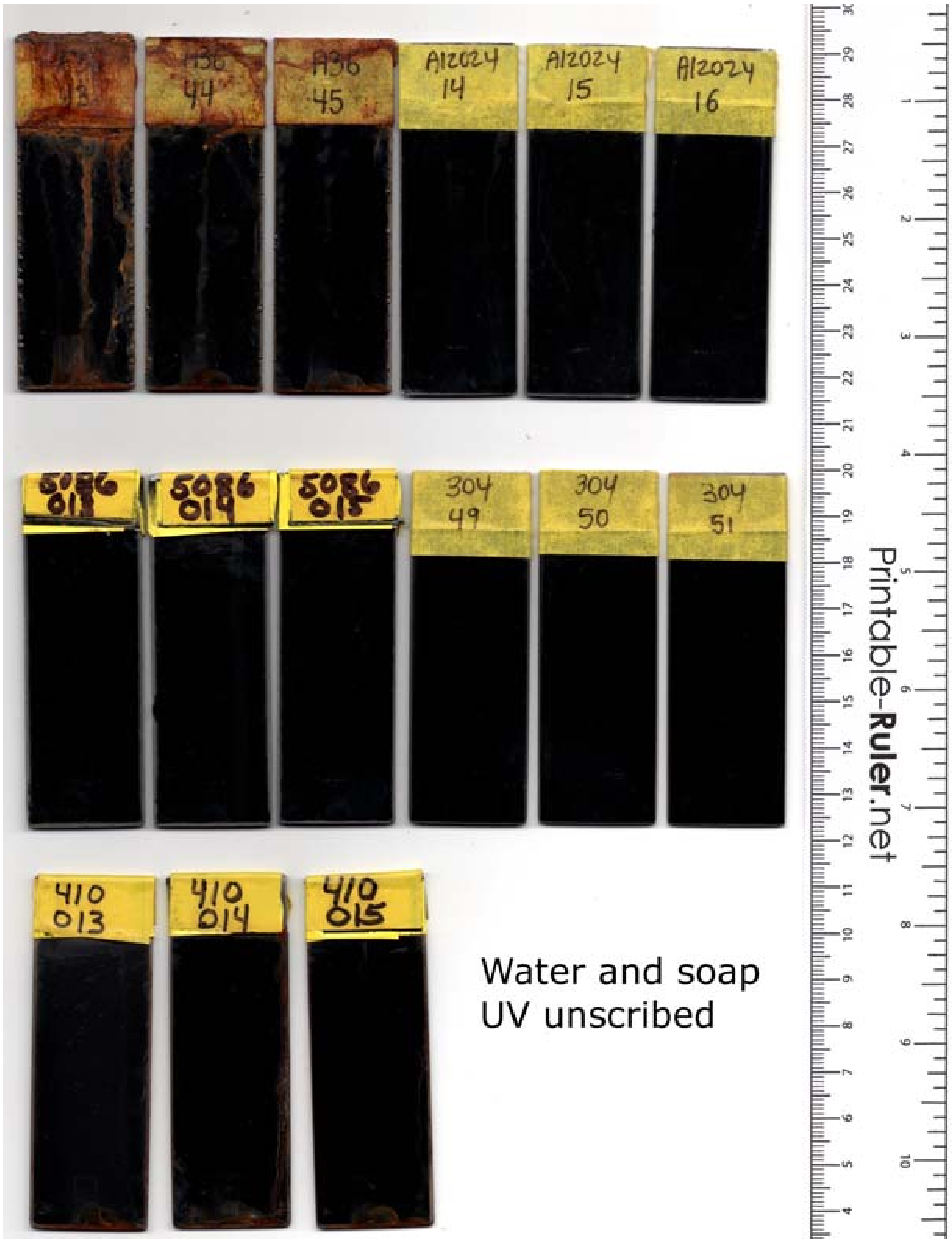

Figure C- 8: Scanned images of metal coupons coated with LCC after 14 days of salt spray exposure. Samples are washed with soap and water every 24 hours.

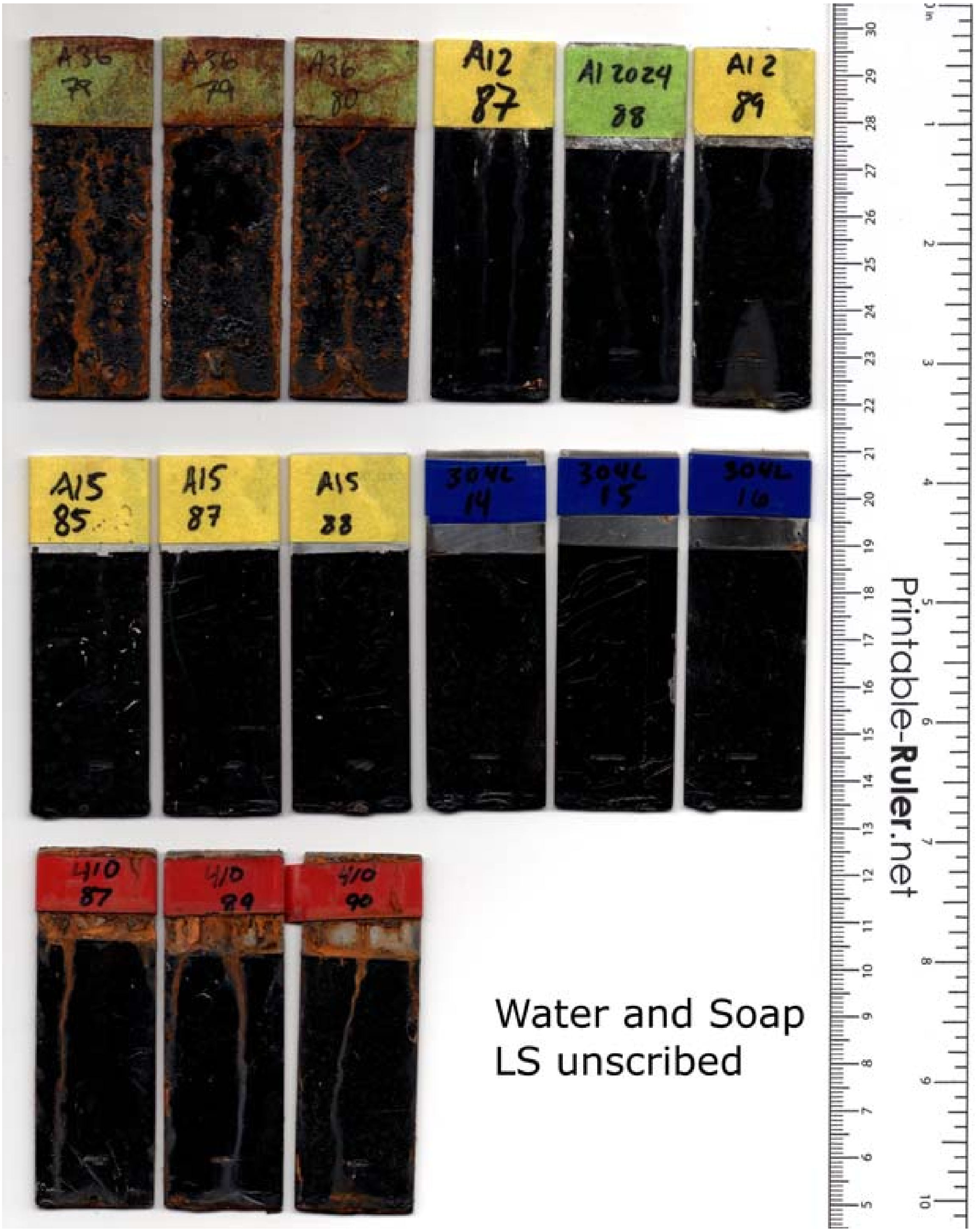

Figure C- 9: Scanned images of metal coupons coated with LubraSeal after 14 days of salt spray exposure. Samples are washed with soap and water every 24 hours.

APPENDIX D

IMAGES FROM CONTACT ANGLE MEASUREMENTS ON BARE CARBON STEEL

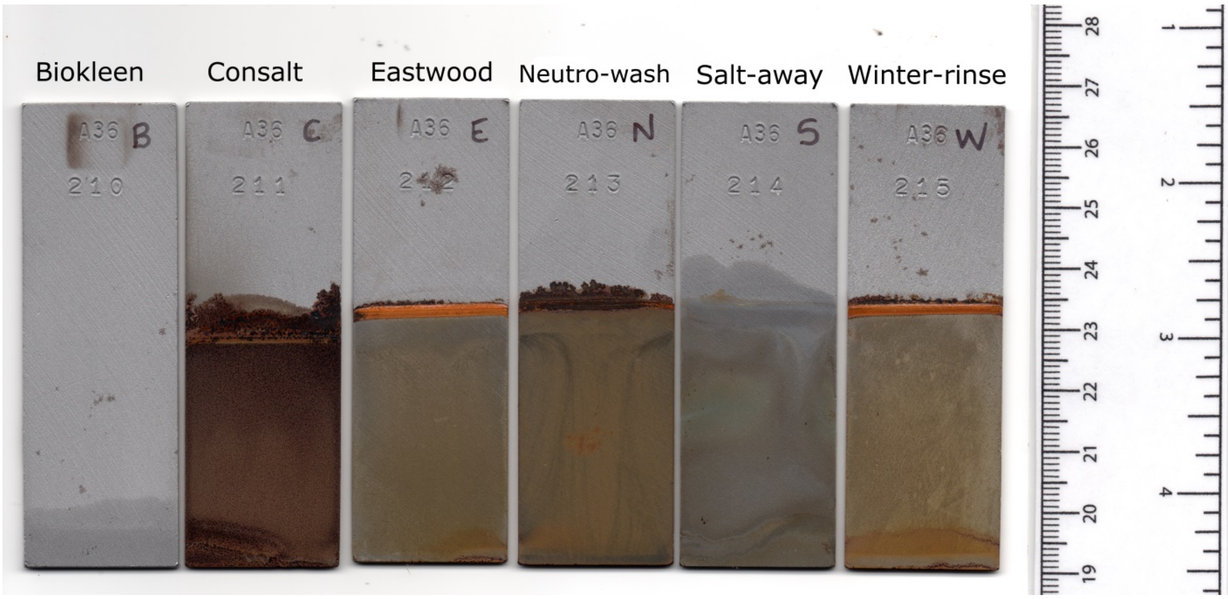

Figure D- 1: Scanned image of A36 after immersion in salt neutralizer solution for 6 hours.

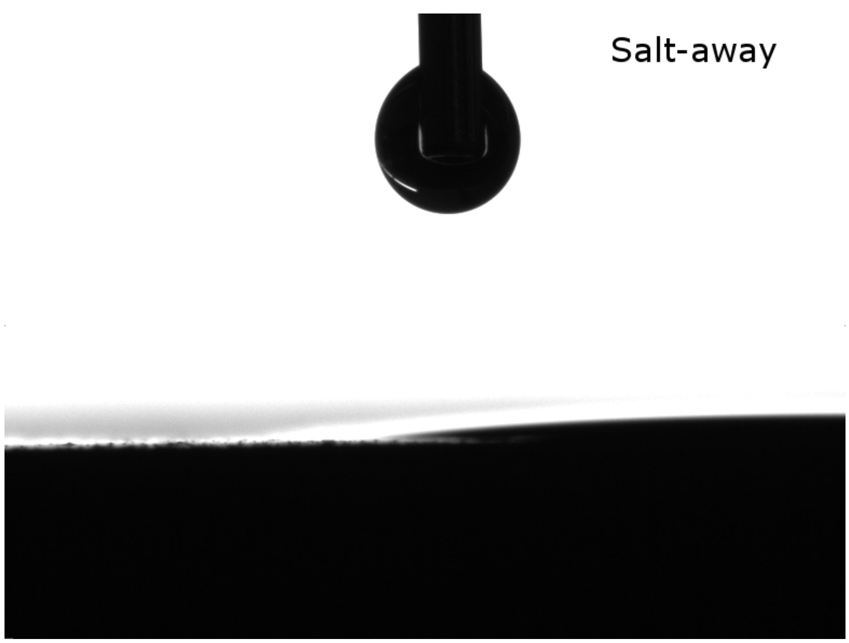

Figure D- 2: Image from contact angle analysis for A36 after a 6 hour immersion in Salt-away.

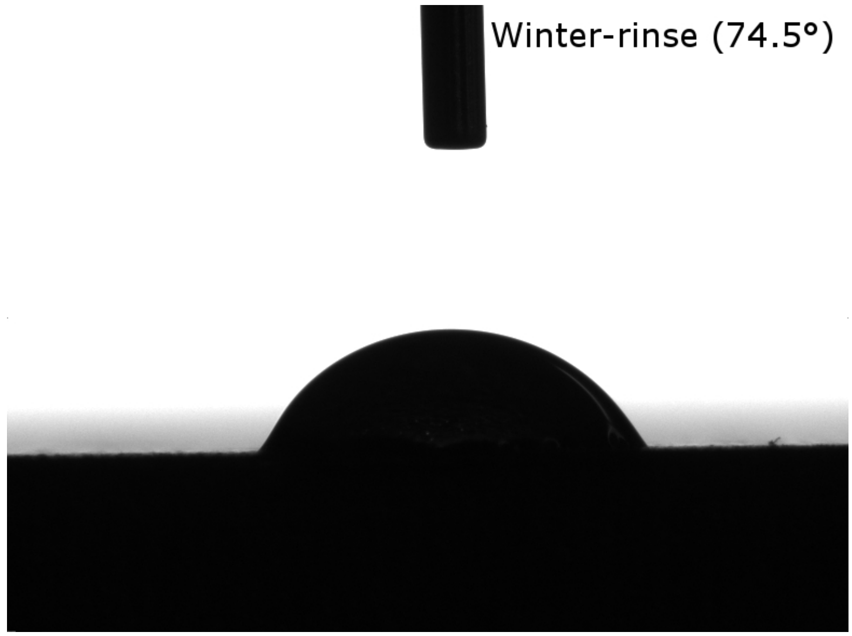

Figure D- 3: Image from contact angle analysis for A36 after a 6 hour immersion in Winter Rinse.

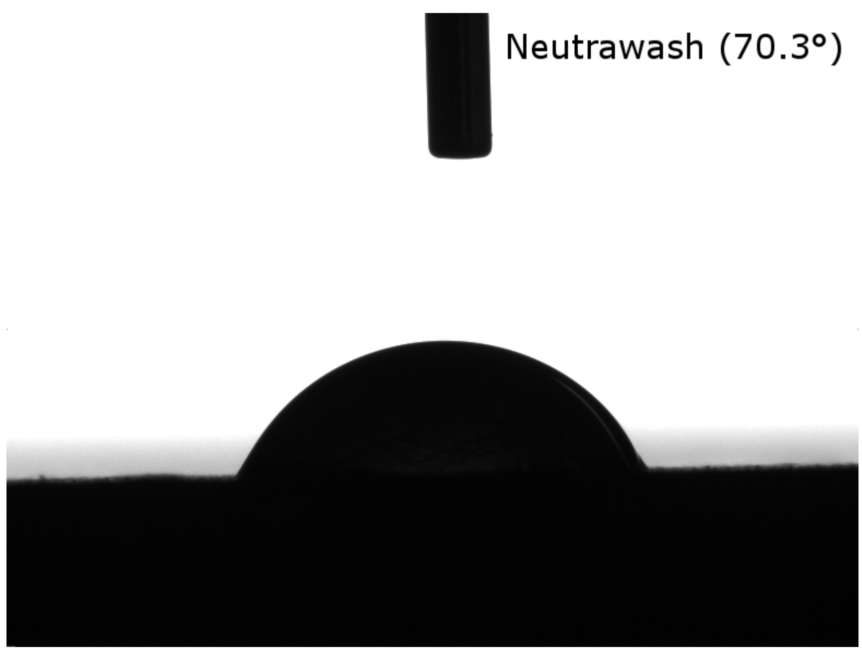

Figure D- 4: Image from contact angle analysis for A36 after a 6 hour immersion in Neutro-wash.

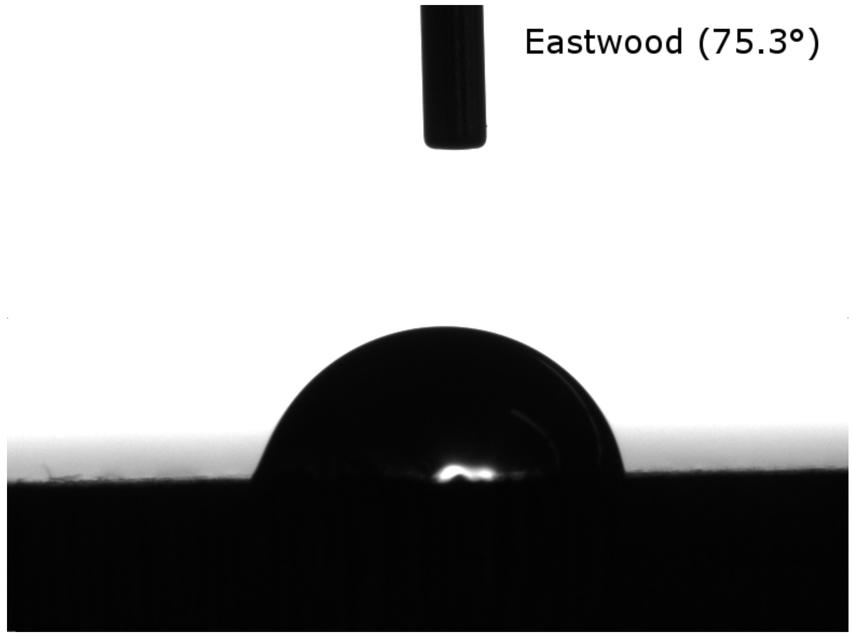

Figure D- 5: Image from contact angle analysis for A36 after a 6 hour immersion in Eastwood.

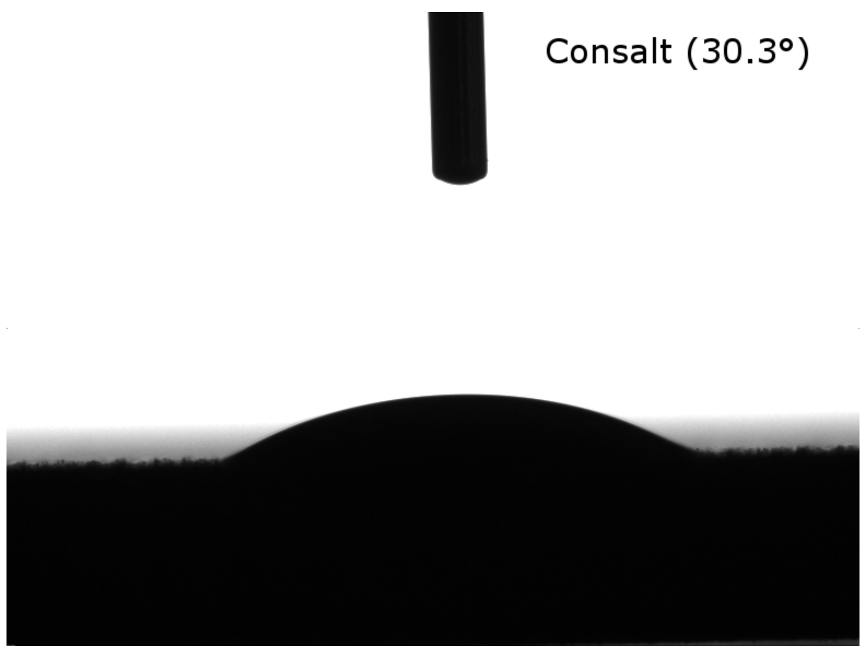

Figure D- 6: Image from contact angle analysis for A36 after a 6 hour immersion in ConSALT.

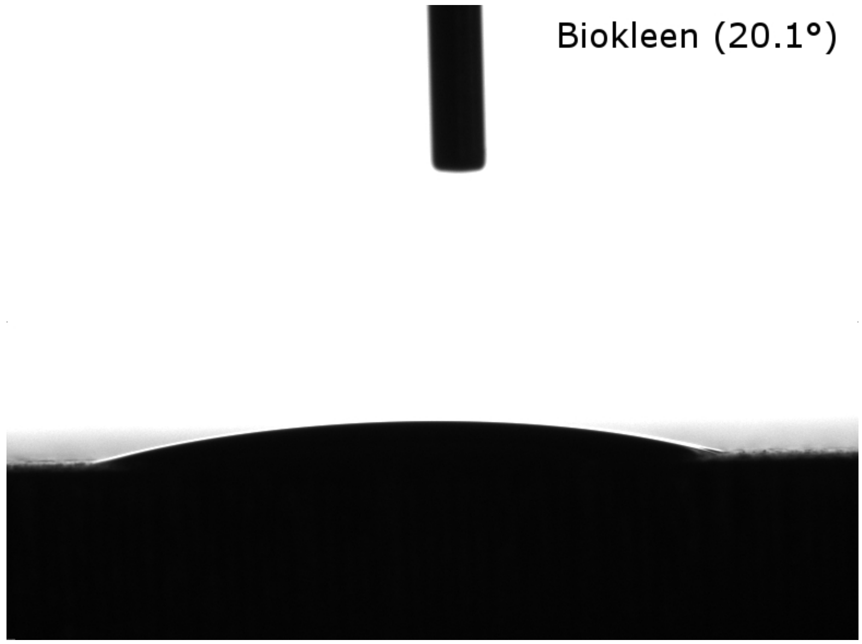

Figure D- 7: Image from contact angle analysis for A36 after a 6 hour immersion in BioKleen.

APPENDIX E

RAW DATA FROM WEIGHT LOSS ANALYSIS ON BARE METAL SAMPLES

Table E- 1: Raw data for weight loss analysis for six salt neutralizers on brass

		Dimensions					Cycles					Mass loss								
SN	Coupon number	Length (cm)	Width (cm)	Thickness (cm)	Total Surface Area (cm^2)	Initial weight (g)	1	2	3	4	5	1	2	3	4	5	Intercept	Mass loss Avg	CR (mmpy)	CR Average
Biokleen	1	2.54	7.64	0.16	42.13	27.35	27.34	27.34	27.34	27.34	27.34	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.07	0.06
	2	2.55	7.64	0.16	42.25	27.34	27.33	27.33	27.33	27.33	27.33	0.01	0.01	0.01	0.01	0.01	0.01		0.05	
	3	2.54	7.64	0.17	42.21	27.30	27.29	27.29	27.29	27.29	27.29	0.01	0.01	0.01	0.01	0.01	0.01		0.05	
	4	2.54	7.64	0.16	42.18	27.38														
conSALT	5	2.54	7.64	0.16	42.12	27.30	27.28	27.28	27.28	27.28	27.28	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.08	0.09
	6	2.55	7.64	0.17	42.32	27.33	27.31	27.31	27.31	27.31	27.31	0.02	0.02	0.02	0.02	0.02	0.02		0.09	
	7	2.54	7.64	0.16	42.07	27.31	27.29	27.29	27.29	27.29	27.29	0.02	0.02	0.02	0.02	0.02	0.02		0.08	
	8	2.54	7.64	0.16	42.19	27.36														
Eastwood	9	2.54	7.64	0.16	42.08	27.33	27.32	27.32	27.32	27.31	27.31	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.07	0.07
	10	2.54	7.64	0.16	42.14	27.35	27.33	27.33	27.33	27.33	27.33	0.01	0.01	0.02	0.02	0.02	0.01		0.07	
	11	2.54	7.64	0.16	42.21	27.35	27.34	27.34	27.34	27.34	27.34	0.02	0.02	0.02	0.02	0.02	0.01		0.07	
	12	2.54	7.63	0.16	42.12	27.30														
Neutro-wash	13	2.55	7.64	0.16	42.23	27.37	27.35	27.35	27.35	27.35	27.35	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.08	0.08
	14	2.54	7.64	0.16	42.20	27.28	27.26	27.26	27.26	27.26	27.26	0.02	0.02	0.02	0.02	0.02	0.02		0.08	
	15	2.54	7.64	0.16	42.11	27.28	27.27	27.27	27.27	27.27		0.02	0.02	0.02	0.02		0.02		0.08	
	16	2.54	7.64	0.16	42.14	27.32														
Salt-away	17	2.54	7.64	0.16	42.09	27.27	27.26	27.26	27.26	27.26	27.26	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.05	0.05
	18	2.54	7.64	0.16	42.14	27.35	27.34	27.33	27.33	27.33	27.33	0.01	0.01	0.01	0.01	0.02	0.01		0.05	
	19	2.54	7.64	0.16	42.13	27.34	28.37	27.37	22.37	27.37	27.37	-1.03	-0.03	4.97	-0.03	-0.02	0.17		0.85	
	20	2.54	7.64	0.16	42.15	27.31														
Winter-rinse	21	2.54	7.64	0.16	42.06	27.35	27.34	27.33	27.33	27.33	27.33	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.07	0.06
	22	2.54	7.64	0.16	42.15	27.37	27.36	27.36	27.36	27.35	27.35	0.01	0.01	0.01	0.01	0.02	0.01		0.06	

	23	2.54	7.64	0.17	42.18	27.30	27.29	27.29	27.29	27.29	27.29	0.01	0.01	0.01	0.02	0.02	0.01		0.06	
	24	2.54	7.64	0.16	42.07	27.35														
Water & Soap	25	2.54	7.64	0.17	42.18	27.35	27.33	27.33	27.33	27.33	27.33	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.06	0.06
	26	2.54	7.64	0.16	42.10	27.31	27.29	27.29	27.29	27.29	27.29	0.01	0.01	0.01	0.01	0.01	0.01		0.06	
	27	2.54	7.64	0.16	42.07	27.32	27.31	27.30	27.30	27.30	27.30	0.01	0.01	0.01	0.01	0.02	0.01		0.05	
	28	2.54	7.64	0.16	42.09	27.34														
Water	29	2.54	7.64	0.16	42.10	27.31	27.30	27.30	27.29	27.29	27.29	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.06	0.06
	30	2.54	7.64	0.16	42.13	27.34	27.32	27.32	27.32	27.32	27.32	0.01	0.01	0.01	0.02	0.02	0.01		0.06	
	31	2.54	7.63	0.16	42.06	27.32	27.30	27.30	27.30	27.30	27.30	0.02	0.02	0.02	0.02	0.02	0.01		0.07	
	32	2.54	7.64	0.16	42.09	27.32														

Table E- 2: Raw data for weight loss analysis for six salt neutralizers on copper

SN	Coupon number	Length (cm)	Width (cm)	Thickness (cm)	Total Surface Area (cm^2)	Initial weight (g)	1	2	3	4	5	1	2	3	4	5	Intercept	Mass loss avg	CR (mmpy)	CR Avg.
Biokleen	1.0	2.5	7.6	0.2	42.2	27.2	27.2	27.2	27.2	27.2	27.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2
	2.0	2.5	7.7	0.2	42.2	27.1	27.1	27.1	27.1	27.1	27.1	0.0	0.0	0.0	0.0	0.0	0.0		0.1	
	3.0	2.5	7.6	0.2	42.2	27.1	27.1	27.1	27.1	27.1	27.1	0.1	0.1	0.1	0.1	0.1	0.1		0.3	
	4.0	2.5	7.7	0.2	42.1	27.1														
conSALT	5.0	2.5	7.6	0.2	42.0	27.1	27.1	27.1	27.1	27.1	27.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2
	6.0	2.5	7.7	0.2	42.2	27.0	27.0	27.0	27.0	27.0	27.0	0.0	0.0	0.0	0.0	0.0	0.0		0.1	
	7.0	2.5	7.6	0.2	42.0	27.1	27.0	27.0	27.0	27.0	27.0	0.1	0.1	0.1	0.1	0.1	0.1		0.3	
	8.0	2.5	7.6	0.2	42.0	27.2														
Eastwood	9.0	2.5	7.6	0.2	42.2	27.1	27.1	27.1	27.1	27.1	27.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2
	10.0	2.5	7.6	0.2	42.2	27.2	27.1	27.1	27.1	27.1	27.1	0.1	0.1	0.1	0.1	0.1	0.1		0.3	
	11.0	2.5	7.6	0.2	42.1	27.1	27.0	27.0	27.0	27.0	27.0	0.0	0.0	0.0	0.0	0.0	0.0		0.2	
	12.0	2.5	7.6	0.2	42.2	27.1														
Neutro-wash	13.0	2.5	7.6	0.2	42.1	27.1	27.1	27.1	27.1	27.1	27.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
	14.0	2.5	7.6	0.2	42.2	27.1	27.1	27.1	27.1	27.1	27.1	0.0	0.0	0.0	0.0	0.0	0.0		0.1	
	15.0	2.5	7.6	0.2	42.2	27.1	27.1	27.1	27.1	27.1	27.1	0.0	0.0	0.0	0.0	0.0	0.0		0.0	
	16.0	2.5	7.6	0.2	42.2	27.1														
Salt-away	17.0	2.5	7.6	0.2	42.2	27.1	27.1	27.1	27.1	27.1	27.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
	18.0	2.5	7.6	0.2	42.2	27.1	27.1	27.1	27.1	27.1	27.1	0.0	0.0	0.0	0.0	0.0	0.0		0.1	
	19.0	2.5	7.6	0.2	42.0	27.0	27.0	27.0	27.0	27.0	27.0	0.0	0.0	0.0	0.0	0.0	0.0		0.1	
	20.0	2.6	7.6	0.2	42.3	27.1														
Winter-rinse	21.0	2.5	7.6	0.2	42.2	27.1	27.1	27.1	27.1	27.1	27.0	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.2	0.1
	22.0	2.6	7.6	0.2	42.2	27.1	27.1	27.1	27.1	27.1	27.1	0.0	0.0	0.0	0.0	0.0	0.0		0.2	
	23.0	2.6	7.6	0.2	42.3	27.1	27.1	27.1	27.1	27.1	27.1	0.0	0.0	0.0	0.0	0.0	0.0		0.0	
	24.0	2.6	7.6	0.2	42.3	27.1														

Water & Soap	25.0	2.5	7.7	0.2	42.2	27.1	27.1	27.1	27.1	27.1	27.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
	26.0	2.6	7.6	0.2	42.4	27.1	27.1	27.1	27.1	27.1	27.1	0.0	0.0	0.0	0.0	0.0	0.0		0.1	
	27.0	2.5	7.6	0.2	42.2	27.1	27.0	27.0	27.0	27.0	27.0	0.0	0.0	0.0	0.0	0.0	0.0		0.1	
	28.0	2.5	7.6	0.2	42.1	27.0														
Water	29.0	2.5	7.6	0.2	42.2	27.1	27.1	27.1	27.1	27.1	27.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2
	30.0	2.5	7.6	0.2	42.3	27.1	27.1	27.1	27.1	27.1	27.1	0.0	0.0	0.0	0.0	0.0	0.0		0.2	
	31.0	2.6	7.6	0.2	42.4	27.1	27.0	27.0	27.0	27.0	27.0	0.0	0.0	0.0	0.0	0.0	0.0		0.1	
	32.0	2.6	7.6	0.2	42.3	27.0														

Table E- 3: Raw data for weight loss analysis for six salt neutralizers on carbon steel (A36)

		Dimensions						Cycles					Mass loss								
SN	Coupon number	Length (cm)	Width (cm)	Thickness (cm)	Thickness (mm)	Total Surface Area (cm^2)	Initial weight (g)	6	7	8	9	10	6	7	8	9	10	Intercept	Mass loss avg	CR (mmpy)	CR Avg.
Biokleen	1.0	2.6	7.6	0.2	0.2	42.4	26.0	25.6	25.6	25.6	25.6	25.6	0.4	0.4	0.4	0.4	0.4	0.4	0.4	2.2	2.2
	2.0	2.5	7.6	0.2	0.2	42.2	26.1	25.7	25.7	25.7	25.7	25.7	0.4	0.4	0.4	0.4	0.4	0.4	0.0	2.2	
	3.0	2.6	7.6	0.2	0.2	42.8	29.2	28.8	28.8	28.8	28.8	28.8	0.4	0.4	0.4	0.4	0.4	0.4	0.0	2.2	
	4.0	2.5	7.6	0.2	0.2	42.7	27.8														
conSALT	5.0	2.6	7.6	0.2	0.2	42.4	25.7	25.2	25.2	25.2	25.2	25.2	0.5	0.5	0.5	0.5	0.5	0.5	0.5	2.6	2.6
	6.0	2.5	7.6	0.2	0.2	42.8	28.9	28.4	28.4	28.4	28.4	28.4	0.5	0.5	0.5	0.5	0.5	0.5	0.0	2.5	
	7.0	2.6	7.6	0.2	0.2	42.6	26.6	26.1	26.1	26.1	26.1	26.1	0.5	0.5	0.5	0.5	0.5	0.5	0.0	2.6	
	8.0	2.6	7.6	0.2	0.2	42.5	25.5														
Eastwood	9.0	2.6	7.6	0.2	0.2	42.5	26.4	25.9	25.9	25.9	25.9	25.9	0.5	0.5	0.5	0.5	0.5	0.5	0.5	2.5	2.5
	10.0	2.6	7.6	0.2	0.2	42.8	29.0	28.6	28.6	28.6	28.6	28.6	0.4	0.4	0.4	0.4	0.4	0.4	0.5	2.4	
	11.0	2.5	7.6	0.2	0.2	42.4	25.6	25.1	24.1	24.1	24.1	24.1	0.5	1.5	1.5	1.5	1.5	-0.3	1.0	-1.8	
	12.0	2.6	7.6	0.2	0.2	42.8	28.8														
Neutro-wash	13.0	2.6	7.6	1.9	0.2	42.8	28.3	27.8	27.8	27.8	27.8	27.8	0.5	0.5	0.5	0.5	0.5	0.5	0.5	2.6	2.5
	14.0	2.5	7.6	1.9	0.2	42.8	28.9	28.5	28.5	28.5	28.5	28.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	2.6	
	15.0	2.6	7.6	1.9	0.2	42.9	28.8	28.4	28.4	28.4	28.4	28.4	0.5	0.5	0.5	0.5	0.5	0.4	0.0	2.4	
	16.0	2.6	7.6	1.7	0.2	42.5	25.8														
Salt-away	17.0	2.5	7.7	1.7	0.2	42.4	26.1	25.8	25.8	25.8	25.8	25.8	0.3	0.3	0.3	0.3	0.3	0.3	0.3	1.7	1.7
	18.0	2.6	7.6	1.9	0.2	42.8	28.2	27.9	27.9	27.9	27.9	27.9	0.3	0.3	0.3	0.3	0.3	0.3	0.0	1.6	
	19.0	2.6	7.6	1.9	0.2	42.9	28.6	28.3	28.3	28.3	28.3	28.3	0.3	0.3	0.3	0.3	0.3	0.3	0.0	1.8	
	20.0	2.6	7.6	1.9	0.2	42.9	28.5														
Winter-rinse	21.0	2.5	7.6	1.7	0.2	42.4	26.4	26.0	26.0	26.0	26.0	26.0	0.4	0.4	0.4	0.4	0.4	0.4	0.4	2.3	2.2
	22.0	2.6	7.6	1.7	0.2	42.4	26.0	25.6	25.6	25.6	25.6	25.6	0.4	0.4	0.4	0.4	0.4	0.4	0.0	2.3	
	23.0	2.6	7.6	1.9	0.2	42.9	28.5	28.1	28.1	28.1	28.1	28.1	0.4	0.4	0.4	0.4	0.4	0.4	0.0	2.2	
	24.0	2.5	7.6	1.8	0.2	42.5	27.7														

Water & Soap	25.0	2.6	7.6	1.9	0.2	42.8	28.4	28.0	28.0	28.0	28.0	28.0	0.4	0.4	0.4	0.4	0.4	0.4	0.4	2.0	2.1
	26.0	2.6	7.6	1.7	0.2	42.6	26.3	25.9	25.9	25.9	25.9	25.9	0.4	0.4	0.4	0.4	0.4	0.4	0.0	2.0	
	27.0	2.6	7.6	1.9	0.2	42.9	28.2	27.8	27.8	27.8	27.8	27.8	0.4	0.4	0.4	0.4	0.4	0.4	0.0	2.2	
	28.0	2.6	7.6	1.9	0.2	42.8	28.8														
Water	29.0	2.6	7.6	1.9	0.2	42.8	28.5	28.1	28.1	28.1	28.1	28.1	0.4	0.4	0.4	0.4	0.4	0.4	0.4	2.0	2.2
	30.0	2.6	7.6	1.9	0.2	43.1	28.6	28.2	28.2	28.2	28.2	28.2	0.4	0.4	0.4	0.4	0.4	0.4	0.0	2.3	
	31.0	2.6	7.6	1.9	0.2	43.4	28.9	28.5	28.5	28.5	28.5	28.5	0.4	0.4	0.4	0.4	0.4	0.4	0.1	2.2	
	32	2.549	7.631	1.750	0.175	42.466	26.4536														

Table E- 4: Raw data for weight loss analysis for six salt neutralizers on aluminum (2024T3)

		Dimensions					Cycles					Mass loss								
SN	Coupon number	Width (cm)	Length (cm)	Thickness (cm)	Total Surface Area (cm^2)	Initial weight (g)	1	2	3	4	5	1	2	3	4	5	Intercept	Mass loss Avg	CR (mmpy)	CR Avg.
Biokleen	13.0	2.6	7.6	0.1	42.0	6.6	6.6	6.6	6.6	6.6	6.6	0.004	0.006	0.006	0.007	0.007	0.004	0.004	0.059	0.062
	14.0	2.6	7.6	0.1	42.2	7.4	7.4	7.4	7.4	7.4	7.4	0.005	0.007	0.007	0.007	0.007	0.005		0.072	
	15.0	2.6	7.6	0.1	41.9	7.3	7.3	7.3	7.3	7.3	7.3	0.004	0.005	0.006	0.007	0.007	0.004		0.056	
	31.0	2.6	7.6	0.1	42.0	7.6	7.6	7.6	7.6	7.6	7.6	0.003	0.005	0.006	0.006	0.007	0.003	0.003	0.048	0.051
	32.0	2.5	7.6	0.1	41.7	7.6	7.6	7.6	7.6	7.6	7.6	0.004	0.006	0.007	0.008	0.008	0.003		0.054	
	33.0	2.6	7.6	0.1	41.8	7.6	7.6	7.6	7.6	7.6	7.6	0.004	0.005	0.007	0.007	0.007	0.003		0.051	
	167.0	2.6	7.6	0.1	41.8	7.7														
conSALT	158.0	2.6	7.6	0.1	41.8	7.8	7.8	7.8	7.8	7.8	7.8	0.006	0.009	0.010	0.011	0.012	0.006	0.006	0.091	0.094
	159.0	2.6	7.6	0.1	41.8	7.8	7.8	7.8	7.7	7.7	7.7	0.007	0.010	0.011	0.012	0.012	0.007		0.104	
	160.0	2.6	7.6	0.1	41.9	7.7	7.7	7.7	7.7	7.7	7.7	0.006	0.009	0.010	0.011	0.011	0.006		0.087	
	161.0	2.6	7.6	0.1	41.9	7.5	7.5	7.5	7.5	7.5	7.5	0.009	0.011	0.013	0.013	0.014	0.008	0.007	0.131	0.104
	157.0	2.6	7.6	0.1	41.9	7.7	7.7	7.7	7.7	7.7	7.7	0.006	0.008	0.010	0.010	0.011	0.005		0.080	
	163.0	2.6	7.6	0.1	41.9	7.7	7.7	7.7	7.7	7.7	7.7	0.007	0.010	0.011	0.012	0.013	0.006		0.101	
	168.0	2.6	7.6	0.1	41.7	7.4														
Eastwood	7.0	2.6	7.6	0.1	42.0	7.4	7.4	7.4	7.4	7.4	7.4	0.003	0.005	0.006	0.007	0.007	0.003	0.003	0.046	0.042
	8.0	2.6	7.6	0.1	42.1	7.3	7.3	7.3	7.3	7.3	7.3	0.003	0.005	0.006	0.006	0.007	0.003		0.049	
	9.0	2.6	7.6	0.1	42.3	7.2	7.2	7.2	7.2	7.2	7.2	0.002	0.004	0.005	0.005	0.006	0.002		0.030	
	25.0	2.6	7.6	0.1	41.7	7.1	7.1	7.1	7.1	7.1	7.1	0.004	0.006	0.006	0.007	0.007	0.004	0.003	0.056	0.041
	26.0	2.6	7.6	0.1	41.7	7.1	7.1	7.1	7.1	7.1	7.1	0.003	0.005	0.006	0.006	0.007	0.002		0.033	
	27.0	2.6	7.6	0.1	41.8	7.4	7.4	7.4	7.4	7.4	7.4	0.002	0.005	0.006	0.007	0.008	0.002		0.033	
	169.0	2.5	7.6	0.1	41.5	7.3														

Neutra-wash	10.0	2.6	7.6	0.1	41.8	7.1	7.1	7.1	7.1	7.1	7.1	0.004	0.005	0.007	0.007	0.008	0.004	0.004	0.057	0.058
	11.0	2.6	7.6	0.1	41.7	6.9	6.9	6.9	6.9	6.9	6.9	0.003	0.006	0.006	0.006	0.007	0.003		0.053	
	12.0	2.6	7.6	0.1	42.5	6.8	6.8	6.8	6.8	6.8	6.8	0.004	0.006	0.007	0.007	0.008	0.004		0.064	
	28.0	2.6	7.6	0.1	42.0	7.5	7.5	7.5	7.5	7.5	7.5	0.004	0.007	0.008	0.008	0.008	0.004	0.002	0.061	0.035
	29.0	2.6	7.6	0.1	41.8	7.6	7.6	7.6	7.6	7.6	7.6	0.001	0.003	0.005	0.005	0.006	0.001		0.015	
	30.0	2.6	7.6	0.1	41.9	7.6	7.6	7.6	7.6	7.6	7.6	0.002	0.004	0.005	0.006	0.006	0.002		0.028	
	170.0	2.6	7.6	0.1	41.5	7.3														
Salt-away	172.0	2.5	7.6	0.1	41.8	7.5	7.5	7.5	7.5	7.5	7.5	0.009	0.014	0.014	0.014	0.015	0.009	0.004	0.146	0.066
	180.0	2.5	7.6	0.1	41.8	7.4	7.4	7.4	7.4	7.4	7.4	-0.005	-0.002	-0.001	0.000	0.000	0.000		0.008	
	182.0	2.6	7.6	0.1	41.8	7.5	7.5	7.5	7.5	7.5	7.5	0.003	0.005	0.007	0.007	0.008	0.003		0.044	
	183.0	2.6	7.6	0.1	41.7	7.2														
Winter-rinse	16.0	2.6	7.6	0.1	41.9	7.2	7.2	7.2	7.2	7.2	7.2	0.004	0.006	0.006	0.007	0.007	0.004	0.004	0.063	0.057
	17.0	2.6	7.6	0.1	42.0	7.2	7.2	7.2	7.2	7.2	7.2	0.004	0.005	0.006	0.007	0.007	0.004		0.058	
	18.0	2.6	7.6	0.1	41.7	7.1	7.1	7.1	7.1	7.1	7.1	0.004	0.006	0.007	0.008	0.008	0.003		0.052	
	34.0	2.6	7.6	0.1	41.8	7.5	7.5	7.5	7.5	7.5	7.5	0.003	0.005	0.006	0.006	0.007	0.002	0.003	0.033	0.047
	35.0	2.6	7.6	0.1	41.7	7.0	7.0	7.0	7.0	7.0	7.0	0.003	0.006	0.007	0.008	0.008	0.003		0.046	
	162.0	2.6	7.6	0.1	41.8	7.5	7.5	7.5	7.5	7.5	7.5	0.004	0.007	0.008	0.009	0.009	0.004		0.062	
	185.0	2.6	7.6	0.1	41.9	7.4														
Water & Soap	4.0	2.6	7.6	0.1	42.2	7.4	7.4	7.4	7.4	7.4	7.4	0.004	0.006	0.007	0.007	0.007	0.004	0.004	0.063	0.055
	5.0	2.6	7.6	0.1	42.1	7.2	7.2	7.1	7.1	7.1	7.1	0.003	0.005	0.006	0.007	0.007	0.003		0.048	
	6.0	2.6	7.6	0.1	42.3	7.3	7.3	7.3	7.3	7.3	7.3	0.004	0.006	0.006	0.007	0.007	0.003		0.052	
	22.0	2.6	7.6	0.1	41.6	7.1	7.1	7.1	7.1	7.1	7.1	0.005	0.007	0.008	0.008	0.009	0.004	0.005	0.064	0.079
	23.0	2.6	7.6	0.1	42.1	7.3	7.3	7.3	7.3	7.3	7.3	0.006	0.008	0.008	0.009	0.009	0.006		0.086	
	24.0	2.6	7.6	0.1	41.7	7.3	7.3	7.3	7.3	7.3	7.3	0.006	0.008	0.008	0.009	0.009	0.006		0.087	
	186.0	2.6	7.6	0.1	41.9	7.5														
Water	1.0	2.6	7.6	0.1	42.0	7.0	7.0	7.0	7.0	7.0	7.0	0.006	0.007	0.008	0.008	0.009	0.006	0.005	0.087	0.078

	2.0	2.6	7.6	0.1	42.4	7.3	7.3	7.3	7.3	7.3	7.3	0.005	0.007	0.007	0.008	0.008	0.005		0.075	
	3.0	2.6	7.6	0.1	41.9	7.4	7.4	7.4	7.4	7.4	7.4	0.005	0.006	0.007	0.007	0.007	0.005		0.071	
	19.0	2.6	7.6	0.1	41.5	6.8	6.8	6.8	6.8	6.8	6.8	0.004	0.007	0.008	0.009	0.009	0.004	0.004	0.065	0.063
	20.0	2.6	7.6	0.1	41.7	7.2	7.2	7.2	7.2	7.2	7.2	0.005	0.006	0.006	0.008	0.008	0.004		0.065	
	21.0	2.6	7.6	0.1	41.9	7.2	7.2	7.2	7.2	7.2	7.2	0.004	0.006	0.007	0.008	0.009	0.004		0.059	
	187.0	2.6	7.6	0.1	41.9	7.5														

Table E- 5: Raw data for weight loss analysis for six salt neutralizers on aluminum (5086)

		Dimensions					Cycles					Mass loss								
SN	Coupon number	Length (cm)	Width (cm)	Thickness (cm)	Total Surface Area (cm^2)	Initial weight (g)	1	2	3	4	5	1	2	3	4	5	Intercept	Mass loss avg	CR (mmpy)	CR Avg.
Biokleen	13	2.57	7.62	0.23	43.90	11.86	11.85	11.85	11.85	11.85	11.85	0.002	0.0028	0.0028	0.0029	0.0029	0.0021	0.0021	0.033	0.033
	14	2.55	7.62	0.23	43.58	11.79	11.79	11.79	11.79	11.79	11.79	0.0023	0.0027	0.0027	0.0028	0.0028	0.0023		0.037	
	15	2.56	7.62	0.23	43.65	11.96	11.96	11.96	11.96	11.96	11.96	0.0019	0.0024	0.0026	0.0026	0.0026	0.0019		0.030	
	31	2.54	7.62	0.23	43.23	11.61	11.61	11.61	11.61	11.61	11.61	0.0012	0.0013	0.0016	0.002	0.002	0.0009	0.0010	0.015	0.016
	32	2.54	7.62	0.23	43.26	11.63	11.63	11.63	11.63	11.63	11.63	0.0014	0.0017	0.002	0.002	0.002	0.0014		0.022	
	33	2.54	7.61	0.23	43.23	11.71	11.71	11.71	11.71	11.71	11.71	0.0008	0.0009	0.0012	0.0012	0.0012	0.0007		0.012	
	168	2.54	7.62	0.22	43.22	11.05													0.000	
conSALT	158	2.55	7.62	0.22	43.50	11.54	11.54	11.54	11.54	11.54	11.54	0.0026	0.0032	0.0034	0.0034	0.0034	0.0027	0.0024	0.042	0.039
	163	2.55	7.62	0.22	43.43	11.31	11.31	11.31	11.31	11.31	11.31	0.0023	0.0036	0.0036	0.0036	0.0037	0.0025		0.040	
	164	2.55	7.61	0.22	43.32	11.24	11.23	11.23	11.23	11.23	11.23	0.0023	0.0027	0.003	0.0032	0.0033	0.0021		0.034	
	160	2.56	7.63	0.22	43.61	11.44	11.43	11.43	11.43	11.43	11.43	0.0034	0.0037	0.0041	0.0041	0.0042	0.0033	0.0027	0.052	0.043
	162	2.56	7.63	0.22	43.46		11.27	11.27	11.27	11.27	11.27								0.000	
	159	2.56	7.63	0.22	43.60	11.53	11.52	11.52	11.52	11.52	11.52	0.0024	0.0028	0.0028	0.0032	0.0034	0.0022		0.035	
	169	2.56	7.64	0.22	43.53	11.19														
Eastwood	7	2.56	7.62	0.24	43.77	12.06	12.06	12.06	12.06	12.06	12.06	0.0020	0.0023	0.0024	0.0026	0.0027	0.0019	0.0051	0.030	0.080
	8	2.55	7.62	0.24	43.67	12.01	12.01	12.01	12.01	12.01	12.01	0.0019	0.0023	0.0023	0.0025	0.0025	0.0019		0.030	
	9	2.57	7.62	0.24	43.94	12.04	12.02	12.02	12.02	12.02	12.02	0.0117	0.0120	0.0122	0.0122	0.0125	0.0116		0.181	
	25	2.54	7.64	0.23	43.56	11.77	11.77	11.77	11.77	11.77	11.77	0.0006	0.0017	0.0020	0.0020	0.0020	0.0007	0.0009	0.011	0.014
	26	2.56	7.61	0.23	43.70	11.74	11.73	11.73	11.73	11.73	11.73	0.0009	0.0016	0.0018	0.0019	0.0021	0.0008		0.013	
	27	2.57	7.62	0.23	43.85	11.71	11.71	11.71	11.71	11.71	11.71	0.0010	0.0016	0.0019	0.0019	0.0019	0.0010		0.016	
	170	2.56	7.63	0.22	43.53	11.19														

Neutro-wash	10	2.56	7.63	0.23	43.72	11.89	11.88	11.88	11.88	11.88	11.88	0.0019	0.0024	0.0024	0.0026	0.0027	0.0019	0.0021	0.029	0.034
	11	2.57	7.60	0.23	43.79	11.83	11.83	11.83	11.83	11.82	11.82	0.0018	0.0023	0.0025	0.0026	0.0026	0.0018		0.028	
	12	2.56	7.60	0.23	43.53	11.80	11.79	11.79	11.79	11.79	11.79	0.0028	0.0031	0.0032	0.0032	0.0033	0.0028		0.044	
	28	2.54	7.61	0.22	43.19	11.47	11.47	11.47	11.46	11.46	11.46	0.0001	0.0006	0.0010	0.0014	0.0014	-0.0001	0.0001	-0.002	0.002
	29	2.55	7.62	0.22	43.32	11.58	11.58	11.58	11.58	11.58	11.58	0.0000	0.0010	0.0012	0.0013	0.0013	0.0001		0.001	
	30	2.55	7.61	0.22	43.23	11.55	11.55	11.55	11.55	11.55	11.55	0.0004	0.0009	0.0013	0.0013	0.0013	0.0004		0.006	
	172	2.54	7.61	0.22	43.20	11.12														
Salt-away	175	2.54	7.62	0.22	43.26	11.28	11.28	11.28	11.28	11.28	11.28	0.0001	0.0027	0.0028	0.0030	0.0030	0.0005	0.0025	0.008	0.040
	178	2.55	7.63	0.21	43.13	10.86	10.86	10.86	10.86	10.85	10.85	0.0040	0.0044	0.0050	0.0055	0.0052	0.0038		0.060	
	179	2.56	7.63	0.21	43.18	10.77	10.77	10.77	10.77	10.77	10.77	0.0039	0.0043	0.0048	0.0050	0.0061	0.0033		0.052	
	180	2.55	7.63	0.22	43.44	11.17														
Winter-rinse	16	2.57	7.62	0.24	43.98	11.90	11.90	11.90	11.90	11.90	11.90	0.0016	0.0022	0.0022	0.0023	0.0025	0.0016	0.0021	0.025	0.033
	17	2.57	7.62	0.23	43.90	11.98	11.98	11.98	11.98	11.98	11.98	0.0025	0.0029	0.0029	0.0030	0.0030	0.0025		0.040	
	18	2.56	7.62	0.24	43.85	12.02	12.02	12.02	12.02	12.02	12.02	0.0023	0.0025	0.0025	0.0027	0.0028	0.0022		0.034	
	34	2.54	7.61	0.23	43.20	11.66	11.66	11.66	11.66	11.66	11.66	0.0009	0.0014	0.0018	0.0019	0.0019	0.0008	0.0008	0.013	0.012
	35	2.54	7.61	0.23	43.22	11.67	11.67	11.67	11.67	11.67	11.67	0.0013	0.0015	0.0018	0.0018	0.0018	0.0013		0.020	
	161	2.56	7.63	0.21	43.23	10.87	10.87	10.87	10.87	10.87	10.87	0.0002	0.0008	0.0010	0.0010	0.0010	0.0003		0.004	
	181	2.56	7.63	0.22	43.45	11.07														
Water & Soap	4	2.56	7.62	0.14	41.89	11.89	11.88	11.88	11.88	11.88	11.88	0.0016	0.0022	0.0022	0.0023	0.0023	0.0017	0.0017	0.027	0.027
	5	2.56	7.62	0.23	43.71	11.96	11.96	11.96	11.96	11.96	11.96	0.0017	0.0016	0.0016	0.0016	0.0017	0.0016		0.026	
	6	2.56	7.62	0.23	43.79	11.09	11.91	11.91	11.91	11.91	11.91	-0.8169	-0.8165	-0.8165	-0.8165	-0.8163	-0.8169		-12.798	
	22	2.54	7.61	0.15	41.62	11.58	11.58	11.58	11.58	11.58	11.58	0.0006	0.0014	0.0014	0.0014	0.0014	0.0008	0.0007	0.013	0.011
	23	2.54	7.62	0.23	43.34	11.83	11.83	11.83	11.83	11.83	11.83	0.0003	0.0015	0.0016	0.0016	0.0016	0.0005		0.008	
	24	2.54	7.62	0.23	43.42	11.76	11.76	11.76	11.76	11.76	11.76	0.0009	0.0012	0.0014	0.0014	0.0015	0.0009		0.014	
	182	2.55	7.65	0.21	43.37	11.00														
Water	1	2.58	7.62	0.23	43.85	11.42	11.42	11.42	11.42	11.42	11.42	0.0023	0.0026	0.0026	0.0026	0.0028	0.0023	0.0021	0.036	0.033

	2	2.57	7.63	0.23	43.83	11.54	11.54	11.54	11.54	11.54	11.54	0.0025	0.0027	0.0030	0.0030	0.0030	0.0025		0.038	
	3	2.57	7.62	0.23	43.90	11.87	11.87	11.87	11.87	11.87	11.87	0.0017	0.0020	0.0020	0.0024	0.0024	0.0016		0.024	
	19	2.54	7.62	0.23	43.38	11.91	11.91	11.91	11.91	11.91	11.91	0.0013	0.0018	0.0018	0.0019	0.0019	0.0014	0.0007	0.021	0.011
	20	2.54	7.61	0.23	43.31	11.59	11.59	11.59	11.59	11.59	11.59	0.0011	0.0014	0.0017	0.0019	0.0019	0.0010		0.015	
	21	2.57	7.62	0.23	43.89	11.67	11.67	11.67	11.67	11.67	11.67	0.0003	0.0006	0.0009	0.0018	0.0019	-0.0002		-0.003	
	185	2.53	7.62	0.21	42.93	10.72														

Table E- 6: Raw data for weight loss analysis for six salt neutralizers on 304L stainless steel

		Dimensions					Cycles					Mass loss								
SN	Coupon number	Length (cm)	Width (cm)	Thickness (cm)	Total Surface Area (cm^2)	Initial weight (g)	1	2	3	4	5	1	2	3	4	5	Intercept	Mass loss avg	CR (mmpy)	CR Avg.
Biokleen	13.0	2.6	7.6	0.1	42.2	21.7	21.7	21.7	21.7	21.7	21.7	0.0007	0.0008	0.0008	0.0008	0.0008	0.0007	0.0006	0.004	0.003
	14.0	2.6	7.6	0.1	42.1	21.7	21.7	21.7	21.7	21.7	21.7	0.0007	0.0006	0.0006	0.0006	0.0006	0.0007		0.004	
	15.0	2.6	7.6	0.1	41.9	20.8	20.8	20.8	20.8	20.8	20.8	0.0004	0.0004	0.0004	0.0005	0.0005	0.0003		0.002	
	31.0	2.6	7.6	0.1	42.1	21.5	21.5	21.5	21.5	21.5	21.5	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0005	-0.002	-0.003
	32.0	2.6	7.6	0.1	42.1	21.5	21.5	21.5	21.5	21.5	21.5	-0.0007	-0.0007	-0.0007	-0.0007	-0.0007	-0.0007		-0.004	
	33.0	2.6	7.6	0.1	42.1	21.5	21.5	21.5	21.5	21.5	21.5	-0.0005	-0.0004	-0.0004	-0.0004	-0.0004	-0.0005		-0.003	
	149.0	2.6	7.6	0.1	41.8	21.7														
conSALT	153.0	2.7	7.6	0.1	43.4	21.7	21.7	21.7	21.7	21.7	21.7	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0006	0.001	0.003
	150.0	2.6	7.6	0.1	42.0	21.8	21.8	21.8	21.8	21.8	21.8	0.0008	0.0008	0.0008	0.0009	0.0009	0.0008		0.004	
	152.0	2.6	7.6	0.1	41.9	21.8	21.8	21.8	21.8	21.8	21.8	0.0010	0.0010	0.0011	0.0011	0.0011	0.0010		0.005	
	154.0	2.6	7.6	0.1	41.8	21.8	21.8	21.8	21.8	21.8	21.8	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002	0.002	0.001
	155.0	2.6	7.6	0.1	42.0	21.6	21.6	21.6	21.6	21.6	21.6	0.0000	0.0002	0.0003	0.0003	0.0004	0.0000		0.000	
	156.0	2.6	7.6	0.1	41.8	21.6	21.6	21.6	21.6	21.6	21.6	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002		0.001	
	160.0	2.5	7.6	0.1	41.8	21.3														
Eastwood	7.0	2.6	7.6	0.1	42.0	21.8	21.8	21.8	21.8	21.8	21.8	0.0009	0.0009	0.0009	0.0009	0.0010	0.0009	0.0008	0.005	0.005
	8.0	2.6	7.6	0.1	42.1	21.7	21.7	21.7	21.7	21.7	21.7	0.0009	0.0009	0.0009	0.0010	0.0010	0.0009		0.005	
	9.0	2.6	7.6	0.1	42.1	21.9	21.9	21.9	21.9	21.9	21.9	0.0008	0.0009	0.0009	0.0009	0.0010	0.0008		0.004	
	25.0	2.6	7.6	0.1	42.2	21.1	21.1	21.1	21.1	21.1	21.1	-0.0003	-0.0002	-0.0002	-0.0002	-0.0002	-0.0003	-0.0002	-0.002	-0.001
	26.0	2.6	7.6	0.1	42.0	21.1	21.1	21.1	21.1	21.1	21.1	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001		-0.001	
	27.0	2.6	7.6	0.1	41.8	20.7	20.7	20.7	20.7	20.7	20.7	-0.0001	0.0000	0.0000	0.0000	0.0000	-0.0001		-4.40E-04	
	165.0	2.6	7.6	0.1	41.8	21.6														
Neutra-wash	10.0	2.6	7.6	0.1	42.2	21.9	21.9	21.9	21.9	21.9	21.9	0.0007	0.0007	0.0007	0.0007	0.0008	0.0007	0.0004	0.004	0.002

	11.0	2.6	7.6	0.1	42.2	21.9	21.9	21.9	21.9	21.9	21.9	0.0004	0.0005	0.0006	0.0006	0.0007	0.0003		0.002	
	12.0	2.6	7.6	0.1	42.3	21.9	21.9	21.9	21.9	21.9	21.9	0.0003	0.0003	0.0003	0.0004	0.0005	0.0002		0.001	
	28.0	2.6	7.6	0.1	42.0	21.0	21.0	21.0	21.0	21.0	21.0	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.002	-0.002
	29.0	2.6	7.6	0.1	42.0	20.9	20.9	20.9	20.9	20.9	20.9	-0.0005	-0.0001	-0.0001	-0.0001	-0.0001	-0.0004		-0.002	
	30.0	2.6	7.6	0.1	42.0	21.1	21.1	21.1	21.1	21.1	21.1	-0.0003	-0.0003	-0.0002	-0.0002	-0.0002	-0.0003		-0.002	
	166.0	2.6	7.6	0.1	42.0	21.6														
Salt-away	167.0	2.6	7.6	0.1	41.8	21.5	21.5	21.5	21.5	21.5	21.5	0.0018	0.0021	0.0021	0.0022	0.0022	0.0018	0.0031	0.010	0.017
	168.0	2.6	7.6	0.1	41.7	21.2	21.2	21.2	21.2	21.2	21.2	0.0044	0.0044	0.0044	0.0045	0.0045	0.0044		0.024	
	169.0	2.6	7.6	0.1	41.9	21.4	21.4	21.4	21.4	21.4	21.4	-0.0064	-0.0064	-0.0064	-0.0062	-0.0062	-0.0065		-0.036	
	170.0	2.6	7.6	0.1	41.8	21.6														
Winter-rinse	16.0	2.6	7.6	0.1	42.1	21.1	21.1	21.1	21.1	21.1	21.1	0.0000	0.0001	0.0001	0.0001	0.0001	2.00E-05	0.0004	0.000	0.002
	17.0	2.6	7.6	0.1	42.2	21.3	21.3	21.3	21.3	21.3	21.3	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007		0.004	
	18.0	2.6	7.6	0.1	42.7	21.3	21.3	21.3	21.3	21.3	21.3	0.0006	0.0007	0.0007	0.0007	0.0008	0.0006		0.003	
	34.0	2.6	7.6	0.1	42.1	21.2	21.2	21.2	21.2	21.2	21.2	-0.0005	-0.0005	-0.0005	-0.0005	-0.0005	-0.0005	0.0005	-0.003	0.003
	35.0	2.6	7.6	0.1	42.2	21.5	21.5	21.5	21.5	21.5	21.5	-0.0005	-0.0005	-0.0005	-0.0004	-0.0004	-0.0006		-0.003	
	151.0	2.6	7.6	0.1	41.8	21.7	21.7	21.7	21.7	21.7	21.7	0.0006	0.0007	0.0008	0.0009	0.0009	0.0005		0.003	
	180.0	2.6	7.6	0.1	41.7	20.8														
Water & Soap	4.0	2.6	7.6	0.1	42.1	22.0	22.0	22.0	22.0	22.0	22.0	0.0006	0.0006	0.0007	0.0006	0.0007	0.0006	0.0006	0.003	0.003
	5.0	2.6	7.6	0.1	42.1	22.0	22.0	22.0	22.0	22.0	22.0	0.0005	0.0008	0.0008	0.0008	0.0008	0.0006		0.003	
	6.0	2.6	7.6	0.1	42.0	21.9	21.9	21.9	21.9	21.9	21.9	0.0007	0.0007	0.0007	0.0008	0.0008	0.0006		0.004	
	22.0	2.6	7.6	0.1	42.0	20.9	20.9	20.9	20.9	20.9	20.9	-0.0005	-0.0005	-0.0005	-0.0005	-0.0005	-0.0005	-0.0005	-0.003	-0.003
	23.0	2.6	7.6	0.1	42.0	21.0	21.0	21.0	21.0	21.0	21.0	-0.0005	-0.0005	-0.0004	-0.0004	-0.0004	-0.0005		-0.003	
	24.0	2.6	7.6	0.1	42.0	21.1	21.1	21.1	21.1	21.1	21.1	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004		-0.002	
	181.0	2.6	7.6	0.1	41.8	20.8														
Water	1.0	2.6	7.6	0.1	42.1	21.8	21.8	21.8	21.8	21.8	21.8	0.0006	0.0007	0.0007	0.0007	0.0008	0.0006	0.0006	0.003	0.003

	2.0	2.6	7.6	0.1	42.1	22.0	22.0	22.0	22.0	22.0	22.0	0.0005	0.0006	0.0006	0.0006	0.0006	0.0005		0.003	
	3.0	2.6	7.6	0.1	42.1	22.0	22.0	22.0	22.0	22.0	22.0	0.0006	0.0008	0.0008	0.0008	0.0008	0.0006		0.003	
	19.0	2.6	7.6	0.1	41.9	21.3	21.3	21.3	21.3	21.3	21.3	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002	-0.0005	-0.001	-0.002
	20.0	2.6	7.6	0.1	41.9	21.3	21.3	21.3	21.3	21.3	21.3	-0.0003	-0.0003	-0.0003	-0.0003	-0.0003	-0.0003		-0.002	
	21.0	2.6	7.6	0.1	42.1	21.8	21.8	21.8	21.8	21.8	21.8	-0.0008	-0.0008	-0.0008	-0.0007	-0.0007	-0.0009		-0.005	
	182.0	2.4	7.6	0.1	40.0	20.6														

Table E- 7: Raw data for weight loss analysis for six salt neutralizers on 410 stainless steel

		Dimensions					Cycles					Mass loss								
SN	Coupon number	Length (cm)	Width (cm)	Thickness (cm)	Total Surface Area (cm^2)	Initial weight (g)	1	2	3	4	5	1	2	3	4	5	Intercept	Mass loss avg	CR (mmpy)	CR Avg.
Biokleen	13.0	2.6	7.6	0.1	42.6	21.4	21.4	21.4	21.4	21.4	21.4	0.0066	0.0075	0.0079	0.0081	0.0081	0.0066	0.0051	0.036	0.029
	14.0	2.6	7.6	0.1	42.4	21.1	21.1	21.1	21.1	21.1	21.1	0.0047	0.005	0.0059	0.0064	0.0066	0.0042		0.023	
	15.0	2.6	7.6	0.1	42.5	21.3	21.3	21.3	21.3	21.3	21.3	0.0048	0.0054	0.0054	0.0057	0.0058	0.0047		0.026	
	31.0	2.6	7.6	0.1	42.1	21.7	21.7	21.7	21.7	21.7	21.7	0.0082	0.0108	0.0114	0.0119	0.0128	0.0079	0.0167	0.045	0.094
	32.0	2.6	7.6	0.1	42.2	21.7	21.7	21.7	21.6	21.7	21.7	0.0082	0.0092	0.1342	0.0106	0.0113	0.0324		0.182	
	33.0	2.6	7.6	0.1	42.1	21.5	21.5	21.5	21.5	21.5	21.5	0.0097	0.0121	0.0124	0.0126	0.0129	0.0099		0.056	
	150.0	2.6	7.6	0.1	42.0	21.4														
conSALT	158.0	2.6	7.6	0.1	42.0	21.4	21.4	21.4	21.4	21.4	21.4	0.0104	0.0137	0.015	0.0165	0.0174	0.0096	0.0093	0.054	0.052
	157.0	2.7	7.6	0.1	43.4	21.3	21.3	21.3	21.3	21.3	21.2	0.0106	0.013	0.015	0.0152	0.0175	0.0095		0.052	
	155.0	2.6	7.6	0.1	42.0	21.3	21.3	21.3	21.3	21.3	21.3	0.0098	0.0118	0.0136	0.0145	0.0156	0.0088		0.050	
	146.0	2.6	7.6	0.1	42.1	21.4	21.4	21.4	21.4	21.4	21.4	0.0122	0.0145	0.0166	0.0179	0.0195	0.0107	0.0107	0.060	0.060
	147.0	2.6	7.6	0.1	42.1	21.3	21.3	21.3	21.3	21.3	21.3	0.0118	0.0143	0.0156	0.017	0.0185	0.0106		0.060	
	148.0	2.6	7.6	0.1	42.1	21.3	21.3	21.3	21.3	21.3	21.3	0.0118	0.0143	0.0156	0.017	0.0185	0.0106		0.060	
	152.0	2.6	7.6	0.1	42.0	21.1														
Eastwood	7.0	2.6	7.6	0.1	42.7	21.6	21.6	21.6	21.6	21.6	21.6	0.0105	0.0118	0.0123	0.0128	0.0131	0.0102	0.0098	0.057	0.055
	8.0	2.6	7.6	0.1	42.6	21.5	21.5	21.5	21.5	21.5	21.5	0.0088	0.0103	0.0114	0.0122	0.0126	0.0082		0.046	
	9.0	2.6	7.6	0.1	42.4	21.4	21.4	21.4	21.4	21.4	21.4	0.0118	0.0135	0.0144	0.0155	0.0161	0.0111		0.062	
	25.0	2.6	7.6	0.1	42.1	21.5	21.5	21.5	21.5	21.5	21.5	0.0114	0.0137	0.0148	0.0152	0.0155	0.0112	0.0099	0.063	0.056
	26.0	2.6	7.6	0.1	42.2	21.6	21.6	21.6	21.6	21.6	21.6	0.0114	0.0138	0.0153	0.0157	0.0159	0.0111		0.063	
	27.0	2.6	7.6	0.1	42.3	21.5	21.5	21.5	21.5	21.5	21.5	0.0077	0.0086	0.0091	0.0096	0.0098	0.0074		0.041	
	165.0	2.6	7.6	0.1	41.8	20.6														
Neutra-wash	10.0	2.6	7.6	0.1	42.2	21.5	21.5	21.5	21.5	21.5	21.5	0.0125	0.0144	0.015	0.016	0.016	0.0122	0.0111	0.068	0.062

	11.0	2.6	7.6	0.1	42.1	21.3	21.3	21.3	21.3	21.3	21.3	0.0109	0.0125	0.0149	0.0161	0.0164	0.0098		0.055	
	12.0	2.6	7.6	0.1	42.2	21.1	21.1	21.1	21.1	21.1	21.1	0.0118	0.0125	0.0131	0.0135	0.0139	0.0114		0.064	
	28.0	2.6	7.6	0.1	42.2	21.8	21.8	21.8	21.8	21.8	21.8	0.0137	0.0145	0.015	0.0156	0.0159	0.0133	0.0123	0.075	0.069
	29.0	2.6	7.6	0.1	42.1	21.7	21.6	21.6	21.6	21.6	21.6	0.012	0.0135	0.0145	0.0156	0.0158	0.0114		0.064	
	30.0	2.6	7.6	0.1	42.1	21.4	21.4	21.4	21.4	21.4	21.4	0.0131	0.0142	0.0154	0.016	0.0168	0.0123		0.069	
	166.0	2.6	7.7	0.1	42.1	20.9														
Salt-away	167.0	2.6	7.6	0.1	42.0	20.9	21.0	21.0	21.0	21.0	21.0	-0.0301	-0.0282	-0.0267	-0.0266	-0.0253	-0.0307	0.0146	-0.173	0.083
	168.0	2.6	7.6	0.1	41.8	20.7	20.7	20.7	20.7	20.7	20.7	0.0167	0.0183	0.0186	0.0191	0.0196	0.0165		0.093	
	169.0	2.6	7.6	0.1	41.8	21.2	21.1	21.1	21.1	21.1	21.1	0.0138	0.015	0.0167	0.0185	0.0185	0.0126		0.072	
	170.0	2.6	7.6	0.1	41.9	20.6														
Winter-rinse	16.0	2.6	7.6	0.1	42.1	20.9	20.9	20.9	20.9	20.9	20.9	0.009	0.01	0.01	0.0102	0.0106	0.0089	0.0078	0.050	0.044
	17.0	2.6	7.6	0.1	42.2	20.9	20.9	20.9	20.9	20.9	20.9	0.0075	0.0084	0.0091	0.0103	0.0115	0.0064		0.036	
	18.0	2.6	7.6	0.1	42.7	21.1	21.1	21.1	21.1	21.1	21.1	0.0086	0.0097	0.0112	0.0117	0.0118	0.0081		0.045	
	34.0	2.6	7.6	0.1	41.9	21.6	21.6	21.6	21.6	21.6	21.6	0.0084	0.0106	0.0114	0.0118	0.0124	0.0082	0.0100	0.046	0.056
	35.0	2.6	7.6	0.1	42.0	21.5	21.5	21.5	21.5	21.5	21.5	0.0085	0.0101	0.0125	0.0137	0.0144	0.0072		0.041	
	156.0	2.6	7.6	0.1	41.8	21.4	21.4	21.4	21.4	21.4	21.4	0.0158	0.0186	0.0213	0.0228	0.0236	0.0145		0.082	
	180.0	2.6	7.6	0.1	41.9	21.0														
Water & Soap	4.0	2.6	7.6	0.1	42.2	21.6	21.6	21.6	21.6	21.6	21.6	0.0088	0.0098	0.0104	0.0109	0.0112	0.0084	0.0083	0.047	0.047
	5.0	2.6	7.6	0.1	42.1	21.4	21.4	21.4	21.4	21.4	21.4	0.0115	0.0122	0.0125	0.0133	0.0136	0.0110		0.062	
	6.0	2.6	7.6	0.1	42.7	21.1	21.1	21.1	21.1	21.1	21.1	0.0071	0.0078	0.0087	0.0113	0.0116	0.0055		0.031	
	22.0	2.6	7.6	0.1	42.1	21.5	21.5	21.5	21.5	21.5	21.5	0.0128	0.0142	0.0144	0.015	0.0155	0.0125	0.0088	0.071	0.049
	23.0	2.6	7.6	0.1	41.9	21.2	21.2	21.2	21.2	21.2	21.2	0.0061	0.0066	0.0069	0.0073	0.0075	0.0058		0.033	
	24.0	2.6	7.6	0.1	42.0	21.4	21.4	21.4	21.4	21.4	21.4	0.0084	0.0092	0.0101	0.0105	0.0109	0.0079		0.045	
	181.0	2.6	7.6	0.1	42.0	21.2														
Water	1.0	2.6	7.6	0.1	42.3	21.3	21.3	21.3	21.3	21.3	21.3	0.0089	0.0099	0.0104	0.0104	0.0107	0.0088	0.0086	0.049	0.048
	2.0	2.6	7.6	0.1	42.6	21.2	21.2	21.2	21.2	21.2	21.2	0.0089	0.0107	0.0113	0.0114	0.0114	0.0090		0.050	

	3.0	2.6	7.6	0.1	42.2	21.4	21.4	21.4	21.4	21.4	21.4	0.0082	0.0093	0.0099	0.0102	0.0102	0.0081		0.045	
	19.0	2.6	7.6	0.1	42.1	21.5	21.5	21.4	21.4	21.4	21.4	0.0047	0.0059	0.0064	0.0068	0.0071	0.0045	0.0060	0.025	0.034
	20.0	2.6	7.6	0.1	42.0	21.1	21.1	21.1	21.1	21.1	21.1	0.0071	0.0095	0.0102	0.0111	0.0117	0.0067		0.038	
	21.0	2.6	7.6	0.1	42.1	21.5	21.4	21.4	21.4	21.4	21.4	0.0076	0.0087	0.0103	0.011	0.0115	0.0068		0.038	
	182.0	2.6	7.6	0.1	42.1	21.1														

APPENDIX F

RAW DATA FROM CMC MEASUREMENTS

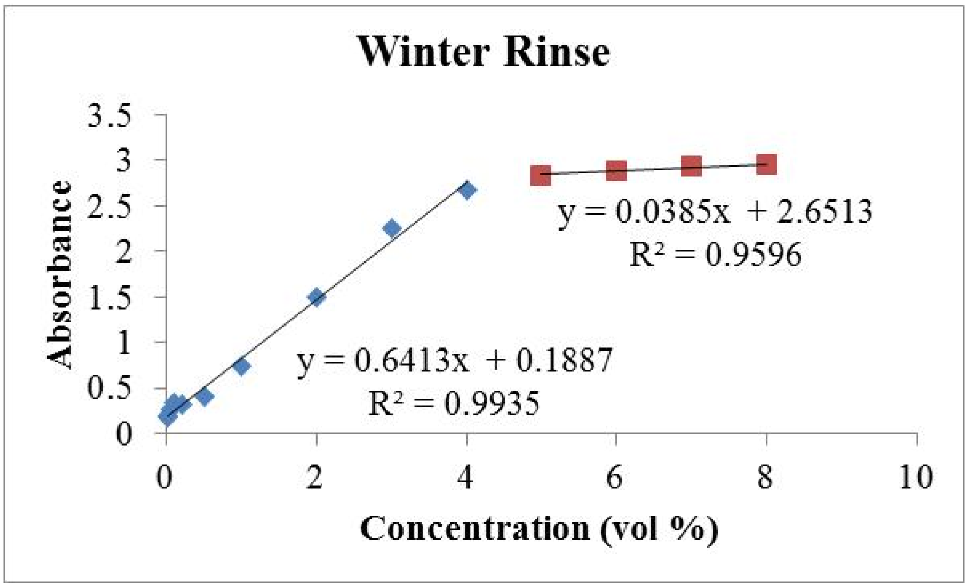

Figure F- 1: Raw data for the determination of CMC for Winter Rinse. CMC is determined by calculating the intersection of the two trend lines above.

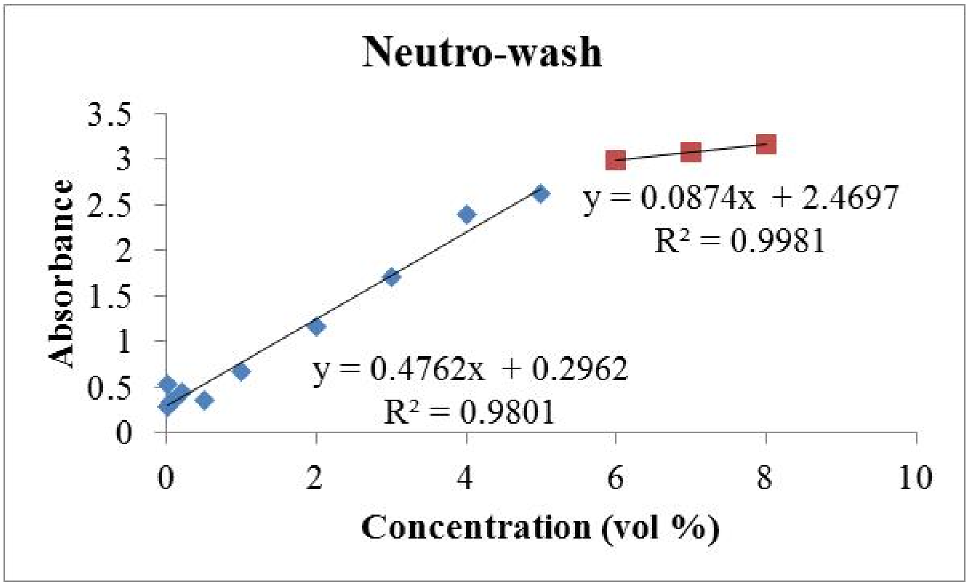

Figure F- 2: Raw data for the determination of CMC for Neutro-wash. CMC is determined by calculating the intersection of the two trend lines above.

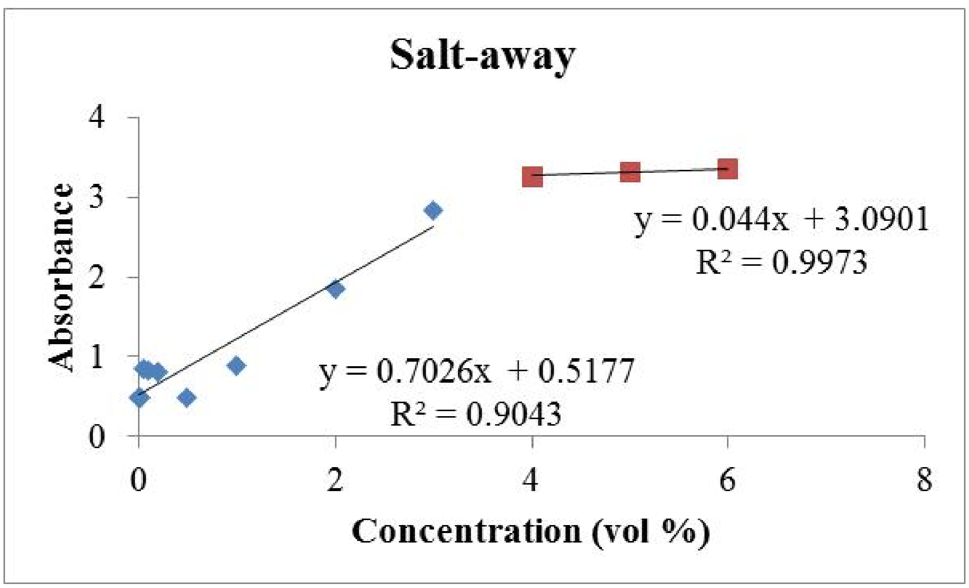

Figure F- 3: Raw data for the determination of CMC for Salt-away. CMC is determined by calculating the intersection of the two trend lines above.

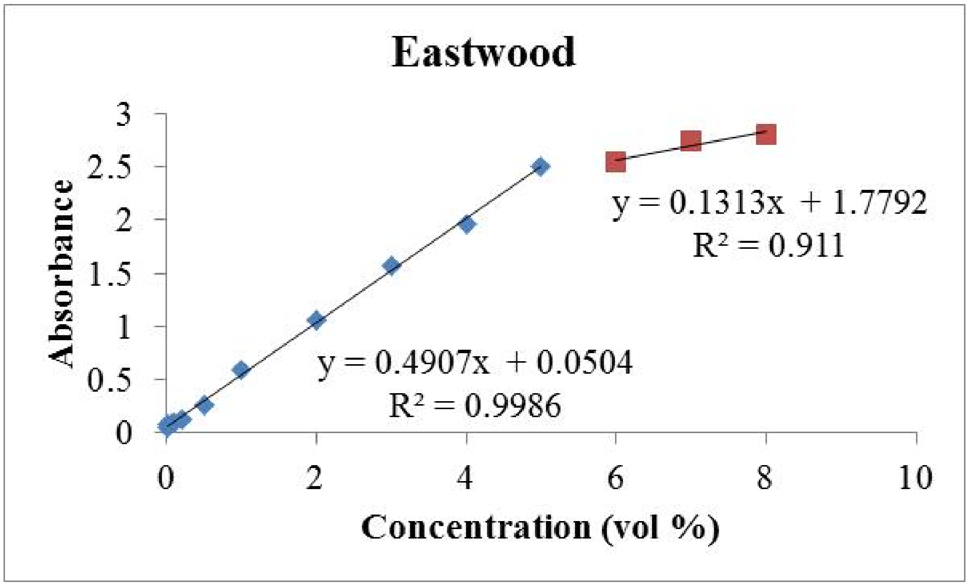

Figure F- 4: Raw data for the determination of CMC for Eastwood. CMC is determined by calculating the intersection of the two trend lines above.

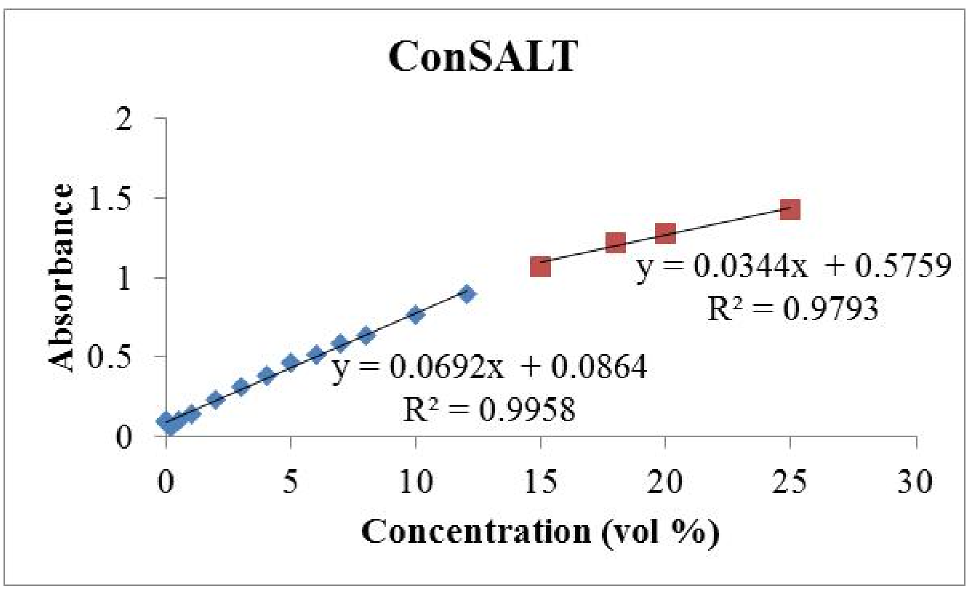

Figure F- 5: Raw data for the determination of CMC for ConSALT. CMC is determined by calculating the intersection of the two trend lines above.

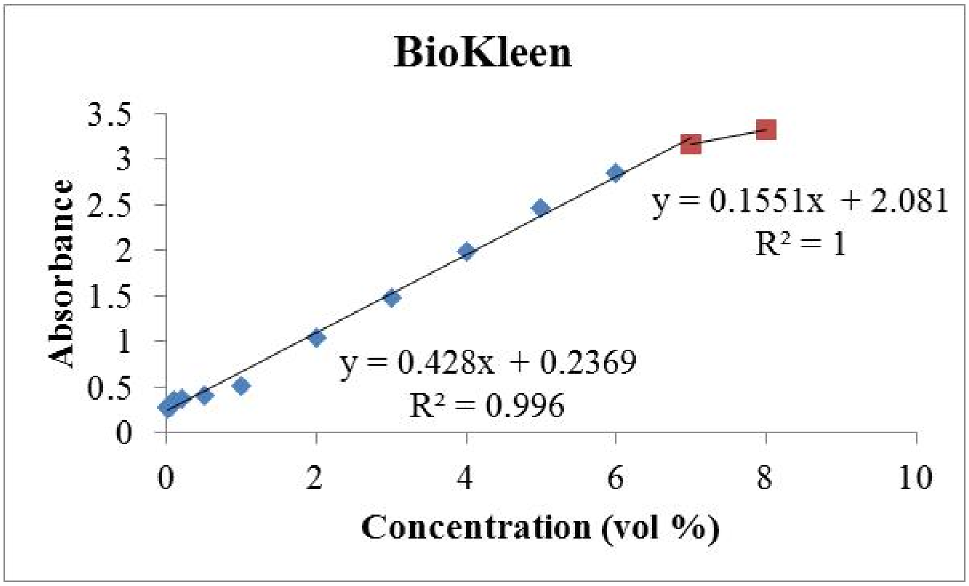

Figure F- 6: Raw data for the determination of CMC for BioKleen. CMC is determined by calculating the intersection of the two trend lines above.

APPENDIX G

RESULTS FROM SAE J2334 TESTING

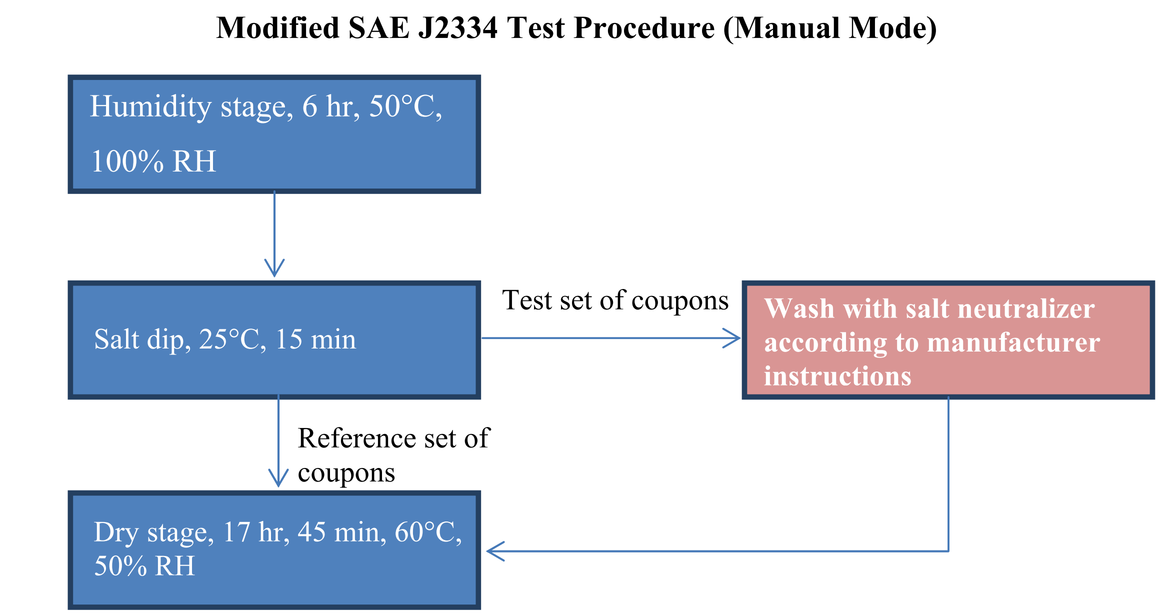

Figure G- 1: Experimental procedure for modified SAE J2334 accelerated corrosion testing.

The modified SAE J2334 procedure is shown in Figure G- 1. SAE J2334 testing was performed on carbon steel A36 for six salt neutralizer applications at both the manufacturer recommended wash concentration and 2.5 times the CMC (Table 3-2). Results from this testing were not included in the main body of this report because the accelerated corrosion rate was not high enough to allow for comparison between different wash methods. Table G- 1 shows the results from this testing. Notice that all corrosion rates are considered excellent and therefore a comparison between wash methods could not be made.

Table G- 1: Mass loss and corrosion rate for SAE J2334 testing

	Mass loss (g)		**Corrosion rate (mmpy)**	
	A36 SUGGESTED	A36 2.5X CMC	A36 SUGGESTED	A36 2.5X CMC
Biokleen	0.001	0.004	0.002	0.005
ConSALT	0.052	0.097	0.078	0.143
Eastwood	0.004	0.022	0.006	0.033
Neutra-wash	0.020	0.031	0.029	0.046
Salt-away	0.002	0.001	0.003	0.002
Winter rinse	0.008	0.021	0.012	0.031
Water & Soap	0.002		0.003	
Water	0.001		0.002	
Hydrochloric Acid (HCl)	0.098		0.145	
Sulfamic Acid (H2S)	0.124		0.184	