ERDC/CERL TR-09-30

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DoD Corrosion Prevention and Control Program

Implementation of Remote Corrosion-Monitoring Sensor for Mission-Essential Structures at Okinawa

Final Report on Project FAR-04 for FY06

L.D. Stephenson, Ashok Kumar, John O'Day,
Benjamin Caldwell, Kevin Kwan, and Bernard C. Laskowski

August 2009

Construction Engineering
Research Laboratory

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Final report

Approved for public release; distribution is unlimited.

Prepared for Office of the Secretary of Defense (OUSD(AT&L))
3090 Defense Pentagon
Washington, DC 20301-3090

Under Military Interdepartmental Purchase Request MIPR6FCERB1020, 20 Mar 06; MIPR6H6AG3CPC1, 15 May 06; and MIPR6HMBHDE097, 31 May 06

Abstract: This project demonstrated innovative remote sensors (LPR sensors) the size of postage stamps which can provide instantaneous corrosion rate data from under a coating. These sensors were installed beneath a coating on a mission-critical metal structure roof in Okinawa, to detect the intrusion of moisture and predict the corrosion rates from the shifts in polarization resistance. With this real-time data capability, early detection of the need for maintenance on the structure can be determined and corrections made, extending the service life of the structure and lowering life-cycle cost. This technology is applicable to metal roofs, water tanks, fences or any metal structures that early detection of corrosion is needed to extend the life of the structure, avoid costly early replacement or avoid complete failure of the structure. Standard coupon tests and electrical resistance (ER) probes provide corrosion rates at a lower cost than the LPR sensors but not instantaneous rates as do the LPR sensors. Standard coupon and ER probes were demonstrated on this project for comparison to LPR corrosion rate data and to obtain atmospheric corrosion rates in this highly corrosive environment.

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Preface

This demonstration was performed for the Office of the Secretary of Defense (OSD) under Department of Defense (DoD) Corrosion Control and Prevention Project FAR-04, "Remote Corrosion Monitoring Sensor for Mission Essential Structures"; Military Interdepartmental Purchase Requests 6FCERB1020, dated 20 Mar 06, 6HMBHDE099, dated 31 May 06 and 6H6AG3CPC1, dated 18 May 06. The proponent was the U.S. Army Office of the Assistant Chief of Staff for Installation Management (ACSIM), and the stakeholder was the U.S. Army Installation Management Command (IMCOM). The technical monitors were Daniel J. Dunmire (OUSD (AT&L) Corrosion), Paul M. Volkman (IMPW-E), and David N. Purcell (DAIM-FDF).

The work was performed by the Engineering and Materials Branch (CEERD-CF-M), Facilities Division (CEERD-CF), U.S. Army Engineer Research and Development Center – Construction Engineering Research Laboratory (ERDC-CERL), Champaign, IL. The ERDC-CERL project manager was Dr. Ashok Kumar. The Associate Project manager was Dr. L.D. Stephenson. Significant portions of this work, involving the LPR sensors, were performed by John O'Day, Benjamin Caldwell, Kevin Kwan and Bernard Laskowsi of Analatom, Inc., Sunnyvale, CA. Craig Meier of Corrosion Control Incorporated performed on site coupon tests and electrical resistance probe tests for corrosion rate comparison to the LPR sensor monitoring system data. James Bushman and Bopinder Phull of Bushman & Associates performed coupon tests of different materials, coatings, and distances from the ocean at Okinawa for comparison to the sensor results.

The support and assistance of personnel at Torii Station, Okinawa, Japan is gratefully acknowledged, especially Daniel Zrna, Engineering, Plans and Services Division Chief, Okinawa Public Works.

This project entailed the demonstration of a postage-stamp sized corrosion rate sensor (LPR) manufactured by Analatom, Inc., to determine the instantaneous corrosion rate of metal under a coating. This report includes the description of the sensors and their operation as well as the lessons learned relating to the collection and analysis of data provided by the sensor system. Also demonstrated for comparison to this sensor and estab-

lishment of atmospheric corrosion rates at Torii Station, were coupons placed near the LPR sensors and at varying distances and varying coatings, from the ocean and Electrical Resistance Probes (ERP) for determination of overall corrosion rates due to the atmosphere in this highly corrosive environment.

At the time this report was prepared, the Chief of the ERDC-CERL Materials and Structures Branch was Vicki L. Van Blaricum (CEERD-CF-M), the Chief of the Facilities Division was L. Michael Golish, (CEERD-CF), and the Technical Director for Installations was Martin J. Savoie (CEERD-CV-ZT). The Deputy Director of ERDC-CERL was Dr. Kirankumar Topudurti and the Director was Dr. Ilker Adiguzel.

The Commander and Executive Director of the U.S. Army Engineer Research and Development Center was COL Richard B. Jenkins and the Director was Dr. James R. Houston.

Executive Summary

This OSD Corrosion Prevention and Control project demonstrated the use of new stamp sized under-film sensors to determine corrosion conditions and moisture intrusion remotely. These Linear Polarization Resistance (LPR) corrosion sensors and system electronics were installed on a metal roof of a critical facility at Torii Station, Okinawa, Japan to perform coating evaluation. For the system to be waterproof and maintenance free in this highly corrosive environment, the electronics enclosures and connectors system components used were carefully chosen for their high Ingress Protection (IP) rating, a measure of water tightness. Test coupons and electronic resistance corrosion probes were also installed near the LPR sensors to compare the capabilities of the different corrosion rate measurement techniques in this highly corrosive environment. One set of coupons also provided corrosion rate data for comparison of coated versus noncoated surfaces, the effect of distance from the ocean and effect of being exposed to rain to wash off salt deposited from the air.

A total of eight LPR corrosion sensors were attached at strategic locations on the metal roof and then only the sensors were painted over with a protective coating and connected to the data acquisition unit. The LPR sensors provided instantaneous corrosion rate data under the coating, providing integrity of the coating monitoring capabilities at any given time. This capability allows detection of corrosive conditions present under the coating so that corrective action may be taken if needed. The use of LPR sensors is particularly useful for monitoring under-film corrosion rates for critical structures in remote locations.

The bare steel coupons tested on the roof and at ground level exhibited an atmospheric corrosion rate from about 1.2 to 2.2 mils per year (mpy). The ER probe indicated about 1.06 mpy. The LPR sensors under the coating indicated a corrosion rate of about 0.118 mils per year, showing the coating was protecting the metal.

The coated coupons tested on ground level indicate the hot-dip galvanized coating performed very well as a protective coating in this corrosive environment. The other coatings did not exhibit as much protection in the scribed areas of the coupons but also did well overall protecting against

corrosion. This test was too short to derive conclusive comparison or to establish suitability of the coatings for long term use in this type of corrosive environment.

Lessons learned related to retrieval of the sensor data. Army personnel at Torii Station were unavailable to periodically download and transmit the collected sensor data back for analysis. Hence it is necessary to automate the transmittal of data back to an office where it can be analyzed.

Unit Conversion Factors

Multiply	By	To Obtain
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
gallons (U.S. liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
mils	0.0254	millimeters
square feet	0.09290304	square meters

1 Introduction

1.1 Problem statement

Corrosion maintenance is a major yearly cost for the Department of Defense (DoD). Managing corrosion is necessary to mitigate the cost burden as well as to sustain readiness of military equipment. Studies performed by both private and government organizations show that each year corrosion costs the U.S. Army $10 billion of which $2 billion are spent for painting and scraping alone.

DoD studies conclude that an optimal approach to handle corrosion involves new inspection and monitoring techniques. Thin smart sensing elements to monitor corrosion have been developed. These sensors were tested and evaluated at ERDC-CERL to validate their capabilities. The results of this evaluation are presented in Appendix A. Because these sensors are thin, they can fit under paints. Because they are smart, they allow for automated Condition Based Maintenance (CBM) on a need basis instead of scheduled maintenance, thus reducing painting frequency and painting costs. This sensor system is sensitive to early stages of corrosion/degradation and such early warning will reduce replacement costs for degraded parts. Furthermore, the system requires less manpower than traditional inspection techniques and results in additional reduced costs for corrosion inspection and maintenance.

Torii Station, a United States Army facility in Okinawa, Japan, has identified severe degradation of coatings on protective structures for mission critical equipment, which will eventually lead to high corrosion rates and failures. Corrosion rate measurement can reveal which areas of a structure need immediate maintenance and which ones will need maintenance later, as well as allow an optimal maintenance schedule to be developed. It will also provide valuable information regarding the performance of the materials selected for use on these structures.

1.2 Objective

The objectives of this work were to:

- Install and evaluate remote monitoring micro Linear Polarization Resistor (LPR) sensors under a coating on a roof to determine their capability to collect and interpret corrosion rate data.
- Install and evaluate coupons and Electrical Resistance (ER) Probes on the roof near the LPR sensors for comparison to the LPR sensors and to collect atmospheric corrosion rate data.
- Install coupons for comparison to the LPR sensors and to collect data related to the effect of coatings on corrosion rate, the difference in corrosion rates on differing metals, the effect of distance from the ocean on corrosion rate, and the effect of surface exposure to rain on corrosion rate, in this highly corrosive environment.

1.3 Approach

The LPR type sensors were analyzed for their applicability to collecting data under a coating on a roof at Torii Station. They were tested in the lab to ensure they would operate as planned under a coating and in a severely corrosive environment. The description of the sensors, the data gathering electronics, software and user interface as well as these tests, are described in Appendix B. Next the physical connection of the sensors to a data collection node was analyzed for its capability to function in this harsh environment. This resulted in redesign of the system electronics node enclosure box and other connection parts to make them more water tight and durable. These design considerations are detailed in Appendix C.

To be able to evaluate and compare the LPR sensor-provided data to standard coupon corrosion rate data; coupon and ER probe tests were designed. Coupon tests were also designed to provide further information relating to the severely corrosive atmospheric effects on metals and coatings at Torii. A description of several corrosion monitoring techniques, including ER probes and coupons, and how they produce corrosion rate data are provided in Appendix D.

2 Technical Investigation

2.1 Project overview

2.1.1 Steel coupon and electrical resistance probes

Twelve C1010 mild steel weight loss coupons (.9”x6”x.125”) were installed on two exposures racks on the roof near the installation site of the LPR sensors. Six electronic resistance corrosion rate probes were installed on the roof in close proximity to the exposure racks and the LPR sensors. The corrosion rates for the coupons and the ER probes were monitored and determined at 2 month intervals over a period of 8 months.

2.1.2 Atmospheric corrosion coupons

Two atmospheric test racks containing test panels (4”x6”x1/8”) of the following materials were installed: bare carbon steel, galvanized steel, zinc-rich epoxy-coated steel, phenolic coated steel and bare type 410 stainless steel. (The steel panels were A36 steel.) The racks were placed at ground level 500 feet and 2000 feet from the ocean. Coupons from these racks were removed, inspected and analyzed at 79, 144, 213, and 247 days.

2.1.3 LPR sensors

Eight remote corrosion monitoring LPR sensors were installed on the roof, all connected to one node. The sensors were connected to a corrosion monitor and test box which facilitated downloading of corrosion data. The system was secured in such a manner that it could withstand, and not be damaged by, high winds and rain.

2.2 Installation of the technology

2.2.1 Steel coupon and electrical resistance probes

The coupons and ER probes were installed on building number 125. The coupons were mounted to an aluminum frame using stainless steel bolts and nylon spacer washers. Stainless steel bolts were used in place of nylon bolts to withstand high wind loads. The coupons were electrically isolated. The resistance probe cables were secured to the roof and run down the outside wall in conduit. The ends of the probe cables were gathered in a NEMA 4X test box. Pictures of the coupons mounted on the roof and the

mounted ER probes are shown in Figures 1 and 2. More details are available in Appendix E.

2.2.2 Atmospheric corrosion coupons

The test panels were all prepared from A36 steel, grit blasted to SSPC-SP5 "white metal" finish with an anchor profile of 2 to 3 mils. For coated panels, the following coating systems were used:

1. Galvanized System - Hot-dip galvanized (Zn coating thickness ~ 3–5 mils).
2. Zinc Rich Primer System - Carboline Carbozinc 859 epoxy zinc primer (3–5 mils) with Carboguard 893SG epoxy topcoat finish (5–7 mils).
3. Phenolic System - Carboline Phenoline 300 primer (8 mils) with Phenoline 302 top coat (8 mils).

The non-coated panels were:

1. Stainless Steel – ASTM Grade 410 with No. 1 mill-finish
2. Carbon Steel – ASTM Grade A-36 with mill-finish



Figure 1. Coupons on rack mounted on roof of Bldg. 125.



Figure 2. ER probes mounted on roof of Bldg. 125.

One side of each coated panel was scribed to simulate mechanical damage commonly encountered in service. Each scribe was ~ 4 inches long and ~ 30 mils wide. The scribed side was exposed facing the ocean.

The Type 410 stainless steel panels were exposed in the No. 1 mill-finish condition.

Hot-dip galvanized steel test racks for mounting the panels, porcelain insulators, and associated fasteners were used. The test racks and test panels were shipped to Torii Station, Okinawa in December 2006. The test panels were mounted on the racks during the same month. The test racks are shown in Figures 3 and 4. More details are provided in Appendix F.



Figure 3. View of one of racks exposed at 500 ft location.



Figure 4. View of location outside Bldg. No. T-113 where second set of test racks was exposed at 2000 ft from the ocean.

2.2.3 LPR sensors

The LPR corrosion sensors and the corrosion monitor were mounted on the roof of building T-125. The sensors, corrosion monitor, cables, and test box were secured to the building in such a manner that they were not damaged by high winds and rain. This involved the following steps:

1. Measured the distance between each LPR sensor and the data acquisition unit.
2. Found secure location to mount LPR sensors.
3. Laid out the LPR sensors on the roof to measure the correct length.
4. Installed connectors to corrosion monitor.
5. Tested the system to ensure proper functionality.
6. Found location for junction box.
7. Installed a junction box for trained personnel to download data once every month.
8. Painted the LPR sensors and performed test.
9. Configured software interface on a PC.
10. Trained personnel to retrieve data.

A long serial cable was installed, with one end attached to the data acquisition unit on the roof and the other end attached to a junction box on the side of the building. The junction box, as shown in Figure 6, houses the other end of the serial cable in a waterproof environment. This allows personnel the option of downloading data collected by the corrosion monitoring system on a periodic basis, if so desired.

A more detailed description of the components of the system and how the sensors were installed is in Appendix G. Figures 5 and 6 show the sensors and interface box as installed.



Figure 5. Installation of LPR corrosion sensors under primer and paint coating.



Figure 6. LPR corrosion sensor system serial interface box.

2.3 Technology operation and monitoring

2.3.1 Steel coupon and electrical resistance probes

A technician returned at 2, 4, 6, and 8 month intervals to document, inspect, remove appropriate coupons for further analysis, and record ER probe data. During each inspection, once photographs had been obtained, three coupons were removed from each exposure rack. The coupons were placed in numbered brown paper envelopes furnished by the coupon manufacturer. The envelopes were sealed and placed in a plastic envelope which was in turn placed in an overnight delivery envelope. The envelopes were express mailed to Metal Samples for analysis.

Metal Samples cleaned and weighed the coupons upon receipt per ASTM Standard G-1 methods. The net metal loss and rate of corrosion was then calculated by the laboratory.

2.3.2 Atmospheric corrosion coupons

Coupons of each type of panel were collected from the two racks at 79, 144, 213, and 247 days following their installation. The test panels were examined visually for overall corrosion resistance/susceptibility and especially at the areas of the steel exposed at the scribes at each of these times. The panels were compared to unexposed control panels during the visual comparisons. Following the final removal of the bare steel panels, the panels were chemically cleaned and their average thickness was measured to determine corrosion loss.

2.3.3 LPR sensors

Data from the LPR sensors was collected, downloaded, and analyzed for the first 24 hours after the sensors were installed, by the technicians who had done the installation. This data indicated the sensors were operating correctly. The sensors were able to detect the increase in moisture during the night and the drying out during the day, from under the coating. After this data collection, a typhoon hit the island. Inspection of the sensors and node connections after this weather indicated the LPR sensor system physically withstood the storm without any damage.

Data were then collected automatically every hour and stored in the node where it could be queried from the box on the side of the building, if desired. The data could be downloaded by connecting a portable computer to the box on the side of the building and querying the system. Although Army personnel at Torii were trained how to download data from the node, their schedules did not allow time to do this.

3 Discussion

3.1 Metrics

The coupons on the roof were analyzed in a lab to determine corrosion rate. The ER probe measurements were taken from the probe reading and converted mathematically into corrosion rate data. This basically involved converting the reading that relates to electrical resistance, which is directly related to metal loss, and converting this into a corrosion rate. See Appendix E for further details.

The bare steel panels used to establish the atmospheric corrosion at ground level were chemically cleaned for measurement using ASTM Standard G-1. Using a micrometer, the panels were then measured to determine thickness loss due to corrosion. The coated panels were visually inspected for degradation and signs of corrosion, i.e., rust colored stains, etc. See Appendix F for further details.

The LPR sensor works like a multiplexed potentiostat. The potential on the metal surface is changed in a controlled manner so that the corresponding current values can be measured as a function of the potential. Through mathematical relationships using Tafel plots and Faradays relation of current flow to mass loss, this information is then converted into a corrosion rate. A more detailed explanation is provided in Appendix H.

3.2 Results

A total of eight LPR corrosion sensors were attached to the metal roof, and then painted over with a protective coating and connected to a data acquisition unit. The system automatically collects data at a rate of at least one reading per hour with the potential of collecting data for a period of 1 year. The system is durable enough to withstand a typhoon.

The 24 hours worth of data collected from the LPR sensors before the typhoon hit is represented in Figure 7. The data tracks with the increase of moisture during night hours and dissipation of moisture during day hours.

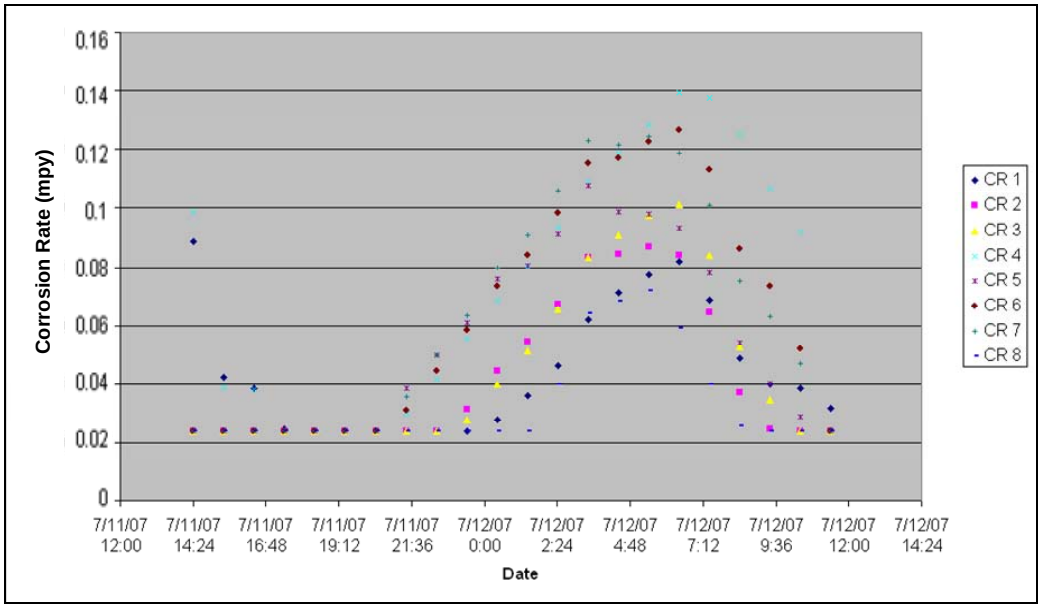


Figure 7. Data collected over 24-hour period.

The coupon and ER probe data collected from the roof near the LPR sensors exhibited similar corrosion rate data. These data are summarized in the following table and the graph in Figure 8. A more detailed explanation of the results is included in Appendix E.

Table 1. Rooftop coupon and ER probe corrosion rates in mils per year.

Month collected	Coupon side 1 (3 coupon average)	Coupon side 2 (3 coupon average)	Average of the six coupons	Electrical Resistance Probe (average of six)
2	1.683	1.554	1.619	1.43
4	1.379	1.401	1.390	1.12
6	1.230	1.246	1.238	1.06
8	1.240	1.200	1.220	1.06

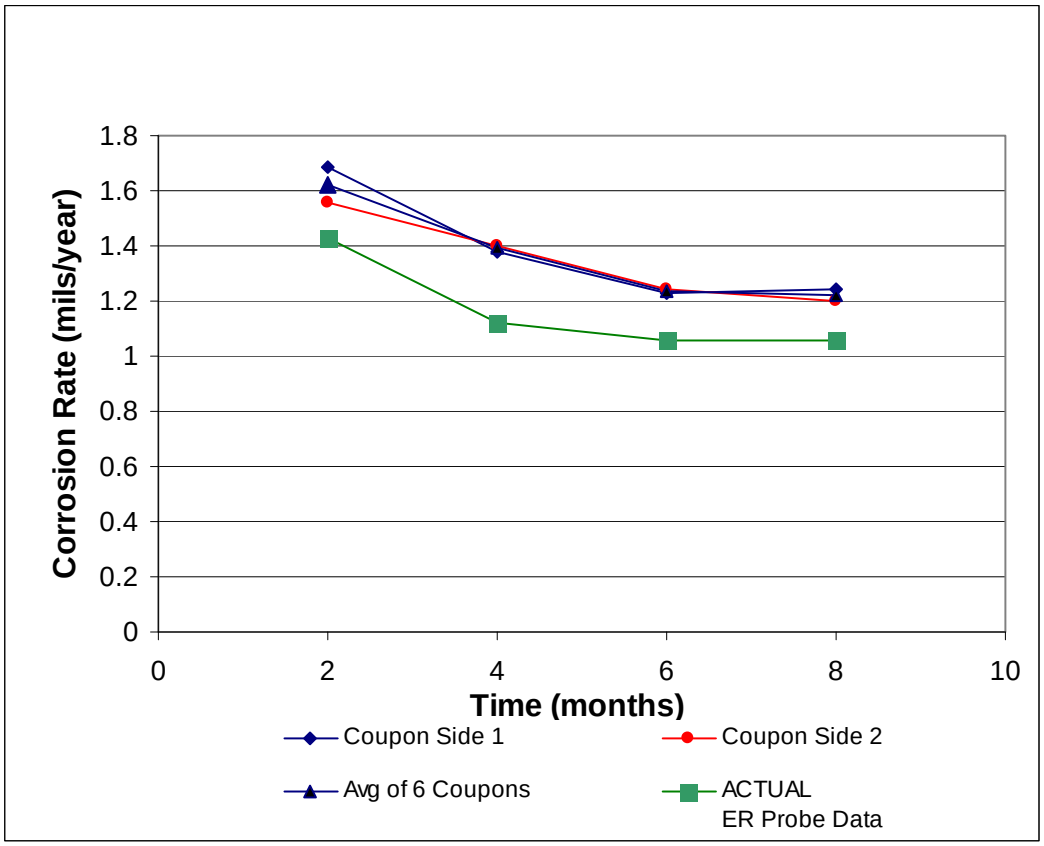


Figure 8. Graph representing roof coupon and ER probe corrosion rates (mils per year vs 2 month interval points).

The atmospheric coupons tests showed little difference between the 500 and 2000 ft distance from the ocean. The atmospheric coupons showed similar corrosion rates for the uncoated coupons at 500 and 2000 feet from the ocean, 2.2 mils per year. The coated coupons showed little corrosion, with the hot-dip galvanized coating performing the best, which included protection of the scribed areas. The coupons did show that the rain washing off the chloride deposits from the air did exhibit slower corrosion than the sides that did not experience the rain wash benefit. The results for the atmospheric coupon tests are detailed in Appendix F.

The corrosion rate data from the coupons and ER probes on the roof showed an unprotected corrosion rate of about 1.1 to 1.2 mils per year, 2.2 mils per year on the uncoated atmospheric coupons at ground level compared to the LPR sensors that were under a film showing a corrosion rate of 0.118 mils per year.

3.3 Lessons learned

One situation encountered at Torii Station was the unavailability of Army personnel to periodically download and transmit the collected sensor data back to Analatom headquarters for analysis. To facilitate data collection for analysis, a more automated data transmittal system is needed.

Three possible scenarios for modifying the sensor node so that it could be communicated with from a remote location were considered. A paper was presented at the Tri-Services Corrosion Conference (December 2007) that provides information related to choosing the best method for automating data transmittal for different sites. This paper is provided in Appendix I. The possibilities considered for Torii were:

1. Ethernet connection to the Internet
2. Cellular modem
3. Satellite modem.

Using an Ethernet connection was ruled out, since it was unclear whether the building on which the sensor node was attached actually had an Internet connection, or if it did, whether an Ethernet cable could be conveniently and securely fastened from the sensor node on the roof to the Internet access point.

The idea of a cellular modem was briefly considered, but there was a question of how easy it would be to interact with the local Japanese cell phone service providers. Dealing with an American-based provider would be easier, but the roaming charges for transmitting from Okinawa might be expensive.

The satellite modem option was selected for further in-depth research. A wireless communication system was also developed in the lab so that the data could be collected from the vicinity of the nodes. However, the lab-tested short distance wireless system was not tested on site. This short distance wireless system is planned for incorporation into the satellite communication system. (The wireless system is described in Appendix J.) This method will, if successful, allow a corrosion sensor node to broadcast its data records from any location in the world to an office for detailed analysis. The proposed satellite modem solution is discussed further in “Recommendations.”

A second issue (but not a problem during this demonstration) has to do with the nature of the cables used to attach to the corrosion sensors. Since the entire test roof was not to be painted, only small patches at strategic places on the roof were coated. This meant that the cabling used to connect to the sensors did not need to be thin enough to paint over; the corrosion sensors themselves were coated, but the cables connecting them to the sensor monitoring electronics were not. The cables used for this part of the demonstration would not have worked well under a coating as they were too thick and would have caused coating problems. Thin cabling is needed that will be able to stay under a coated surface, without breaking the surface and causing moisture to seep under the protective coating.

4 Economic Summary

The assumptions and calculations used in the return on investment (ROI) analysis are presented below. It is based on propagation of this sensor technology and lessons learned to additional roofs and buildings within the Army. This analysis validates the ROI in the Project Management Plan (ROI=14.1). It is further noted that this innovative sensor can be used for any metallic component used in Army facilities and utilities, which must be routinely painted in order to reduce the maintenance costs and prevent pre-mature failure, and this would tend to increase the ROI.

Alternative 1: The roof on the building at Torii Station, Okinawa, Japan will require replacement at a cost of $100K in Year 15. In addition, there are 20 additional roofs in the same condition in severely corrosive environments that will require replacement from Year 16 –Year 19 (over a 4-year period) at 5 roofs per year, as shown in Table 1. The current maintenance costs are only $2K every 10 years for each roofing system, as the roofing system is not well maintained. The total baseline costs of Alternative 1 are shown in Table 1, and also in the ROI spreadsheet under “Baseline Costs.” In addition, equipment inside the building will be damaged at $200K (see Table 2) for each of the leaking roofs in the year before it is replaced. The roof is replaced in the following year, at a cost of $100K for each roof. In the year in which the roofs are replaced, the cost of disruption of operations is estimated conservatively to be $2M for each roof, also shown in Tables 1 and 2. The total additional costs are shown under “cost of equipment damage & cost of disruption of operations” in Tables 1 and 2, and under “New System Benefits” in the ROI spreadsheet. The new roofing systems will use the LPR technology to indicate when maintenance must be performed and the cost of maintenance is shown for the replaced roofs under “Baseline costs,” beginning in Year 20.

Alternative 2: The cost of this project to implement LPR sensors under coatings is $900K in Year 1. The implementation of LPR sensors for the first roof at $140K, is included in the cost of this project. Implementation cost for each of the 20 additional LPR sensors under roofing coatings from Year 2 to Year 5 (over a 4-year period), at 5 roofs per year, at $140K for each roof , are shown in Table 1, and in the ROI Spreadsheet under "New system Costs."

The LPR sensors will indicate when the roofing coating requires maintenance due to coating degradation. Maintenance costs of the roofing coatings are shown under “New System Costs” at $5K per roof at an average of every 5 years. The necessity of replacing the leaking roofs under Alternative 1 and “cost of equipment damage & cost of disruption of operations” will be avoided.

The estimated ROI for implementing the LPR sensors is estimated to be 14.2.

Table 2. Cost and savings information for ROI investment.

Return on Investment Calculation

Investment Required			**900,000**
Return on Investment Ratio	**14.18**	**Percent**	**1418%**
Net Present Value of Costs and Benefits/Savings	**2,344,875**	**15,103,626**	**12,758,751**

A Future Year	B Baseline Costs	C Baseline Benefits/Savings	D New System Costs	E New System Benefits/Savings	F Present Value of Costs	G Present Value of Savings	H Total Present Value
1							
2	2,000		140,000		122,276	1,747	-120,529
3			700,000		571,410		-571,410
4			700,000		534,030		-534,030
5	10,000		700,000		499,100	7,130	-491,970
6			700,000		466,410		-466,410
7			5,000		3,114		-3,114
8	10,000		25,000		14,550	5,820	-8,730
9			25,000		13,598		-13,598
10			25,000		12,708		-12,708
11	10,000		25,000		11,878	4,751	-7,127
12			5,000		2,220		-2,220
13			25,000		10,375		-10,375
14	2,000		25,000	200,000	9,695	78,336	68,641
15	100,000		25,000	3,000,000	9,060	1,123,440	1,114,380
16	500,000		25,000	11,000,000	8,468	3,895,050	3,886,583
17	500,000		5,000	11,000,000	1,583	3,640,900	3,639,317
18	500,000		25,000	11,000,000	7,398	3,402,850	3,395,453
19	500,000		25,000	10,000,000	6,913	2,903,250	2,896,338
20	5,000		25,000		6,460	1,292	-5,168
21	25,000		25,000		6,038	6,038	
22	25,000		5,000		1,129	5,643	4,514
23	25,000		5,000		1,055	5,273	4,218
24	25,000		25,000		4,928	4,928	
25	5,000		25,000		4,605	921	-3,684
26	25,000		25,000		4,305	4,305	
27	25,000		25,000		4,023	4,023	
28	25,000		5,000		752	3,760	3,008
29	25,000		25,000		3,515	3,515	
30	5,000		25,000		3,285	657	-2,628

	Old System Costs			New System Costs			
Year	Cost of Roof Replacement ($)	Current Maintenance Costs ($)	TOTAL ($)	Cost of Sensors ($)	New system Maintenance Costs ($)	TOTAL ($)	Avoided cost of Damage & Disruption of Operations ($)
1			0	140,000		140,000	
2		2,000	2,000	700,000		700,000	
3			0	700,000		700,000	
4			0	700,000		700,000	
5		10,000	10,000	700,000		700,000	
6			0		5,000	5,000	
7			0		25,000	25,000	
8		10,000	10,000		25,000	25,000	
9			0		25,000	25,000	
10			0		25,000	25,000	
11		10,000	10,000		5,000	5,000	
12			0		25,000	25,000	
13			0		25,000	25,000	
14		0	0		25,000	25,000	200,000
15	100,000		100,000		25,000	25,000	3,000,000
16	500,000		500,000		5,000	5,000	11,000,000
17	500,000		500,000		25,000	25,000	11,000,000
18	500,000		500,000		25,000	25,000	11,000,000
19	500,000		500,000		25,000	25,000	10,000,000
20	5,000		5,000		25,000	25,000	
21	25,000		25,000		5,000	5,000	
22	25,000		25,000		25,000	25,000	
23	25,000		25,000		25,000	25,000	
24	25,000		25,000		25,000	25,000	
25	5,000		5,000		25,000	25,000	
26	25,000		25,000		5,000	5,000	
27	25,000		25,000		25,000	25,000	
28	25,000		25,000		25,000	25,000	
29	25,000		25,000		25,000	25,000	
30	5,000		5,000		25,000	25,000	

Table 3. Roof replacement schedule for development of ROI.

	Roof Replacement Schedule/Damage due to Leaking Roofs						TOTAL
COSTS/ROOF/YEAR	Number of Roofs>>	1	5	5	5	5	Damage Cost & Disruption of Operations ($)
	Year						
	13	0	0	0	0	0	0
	14	200,000	0	0	0	0	200,000
	15	2,000,000	200,000	0	0	0	3,000,000
	16	0	2,000,000	200,000	0	0	11,000,000
	17	0	0	2,000,000	200,000	0	11,000,000
	18	0	0	0	2,000,000	200,000	11,000,000
	19	0	0	0	0	2,000,000	10,000,000
	20	0	0	0	0	0	0

5 Conclusions and Recommendations

5.1 Conclusions

The averaged realized corrosion rate for all six coupons (9 x 6 x 0.125 in.) on the roof at 8 months was 1.22 mils per year (mpy). The averaged realized corrosion rate obtained by the ER probes on the roof at 8 months was 1.06 mpy. The corrosion rate as measured by thickness loss on the bare carbon steel coupons (4 x 6 x 0.125 in.) placed on a rack at ground level near the building for 8 months was 2.2 mils per year.

The atmospheric coupon test indicates there is a slowing of corrosion rate for surfaces exposed to rain wash versus not having the chloride deposited from the air being washed off. The coated coupons corrosion analysis for this short-term test indicates that all of the tested coatings protected the metal, but the hot-dip galvanized coating performed best, including protection in the scribed areas. (More details are provided in Appendix F.)

The corrosion rate of steel under the coating, as measured by the stamp size Analatom linear polarization resistance sensor, was 0.118 mils per year. This corrosion rate is an order of magnitude less than the bare steel corrosion rate, as would be expected for a coated surface vs. a bare surface. The Analatom LPR sensors measured the microscopic corrosion rate of carbon steel under the coating and were sensitive to ambient temperature and moisture depending on the time of the day. The extreme sensitivity of the corrosion current or corrosion rate, as measured by the LPR sensor, to ambient temperature and moisture could be detected and recorded by the sensor system.

The LPR sensor system installation and system activation were successful. Initial data collection accurately represents corrosive behavior that would be expected from the specific Okinawa Island environmental conditions. During the evening and nighttime hours, the LPR corrosion sensors under the primer and paint coating were able to detect increased moisture levels, which dissipate as the sun comes out and the daytime progresses. Furthermore the installed system physically survived the high winds of a Category 3 typhoon.

The current LPR sensor data collection process required somebody onsite to download data from the junction box connected to the sensor data collection node. The data collection process needs to be modified to alleviate the necessity of onsite personnel to download the data.

The LPR sensors provide *instantaneous* corrosion rate data at any given time and from beneath a coating, if desired. Also, the LPR sensors report instantaneously when corrosive conditions are present underneath a coating so that corrective action may to be taken (for example, when coating degradation allows moisture to infiltrate). The ER probes and coupons provide corrosion rate data at less cost if the time frame for data acquisition is longer and you do not need the corrosion rate under a coating, in a tight-fit location, or where coupons and ER probes are not practical.

5.2 Recommendations

5.2.1 Applicability

The LPR sensors provide immediate corrosion rate data. In order to make the LPR sensor systems more useful, the data collection process should be augmented to allow remote access to the data via one of the ways presented in the approach: (1) Ethernet connection, (2) cellular modem, (3) satellite modem. Depending on the site, these different methods are all viable. For Okinawa the best method appears to be via satellite modem. It is recommended that the satellite modem be used to transmit the data back to Analatom's office for analysis if any further work is done at Okinawa. This alleviates the necessity of onsite personnel to take the time to download and transfer the data for analysis.

The connection of the sensors to the sensor node should be made with thinner wire cabling that can be totally coated under the surface without causing problems, i.e., coating cracks. The new design needs to incorporate a thin corrosion sensor at the end of a long, flexible strip of flex circuitry, which will also need to be designed for better electrical noise shielding. The entire assembly needs to be capable of being painted over, allowing for a large array of sensors to be deployed on a roof or structure without disturbing the protective coating applied over it.

It is recommended that the sensors as modified above with the satellite modem upload and the thin connecting cabling be further evaluated for ease of installation and use. They could be used to evaluate four new coat-

ing materials at Okinawa. Two sensors under each of the four coatings would provide good corrosion rate data for comparison of coatings performance.

Depending on the time allowed to determine corrosion rate and the application to be tested, the LPR, ER probes, and coupons all provide good corrosion rate data. For quick corrosion rate data or under a coating, the LPR sensors are a good choice, although they are more expensive. If more time is allowed, the ER probes provide good atmospheric corrosion rate data without needing lab analysis support. The cheapest method is to use coupons, but they require lab analysis and exposure time to attain realistic data.

The choice of which method to use depends on the time frame allowed, the criticality of obtaining the information quickly, whether you need the corrosion rate under a coating, and the ROI for using the method on the structure.

Other engineering structures at Okinawa recommended to be evaluated for ROI to be monitored by an LPR corrosion sensor system are communication dish stalks and piping and new coatings used to protect air conditioning systems. Details of these recommendations are given in Appendix K.

The LPR sensors could also be used to help establish the corrosivity of specific installation environments, which would tie into the proper selection of materials for structures at those sites. The effective use of sensors is not in placing them on all locations as, in most cases, no data can be gained that could not be obtained through visual inspection. The key is to place sensors in critical areas where inspection is difficult to implement (such as in remote locations where travel is difficult) and failure is costly and possibly hazardous.

5.2.2 Implementation

The technologies demonstrated and implemented under this project are recommended for Army and DoD installations where ROI justifies their use. A list of the components required for installation and how to install a LPR sensor system on a coated metal roof as was done at Torii Station is provided in Appendix G. The specification sheets for these LPR sensors are in Appendix L.

It is recommended that the three methods of determining corrosion rate, and therefore corrosivity of the environment, presented in this report be added as a section of the "Materials Selection Guide for Army Installations Exposed to Severely Corrosive Environments." This addition will provide the sites with a method to determine corrosivity of the environment and therefore the information needed to select the proper material. Selection of which method to use to determine the corrosivity of the environment depends on the time constraints and resources available. If the corrosion rate under a film is needed, the LPR sensors can provide instantaneous corrosion rate information. If several months are available to obtain the atmospheric corrosion rate, the ER probes are less expensive and a good choice. In any case, however, only LPR sensors can provide accurate under-film measurement of the corrosion rate. If longer times are available, the coupons provide good corrosion rate information. The specifications provided by the manufacturers of these devices should be followed for installation, use, and data analysis to obtain accurate corrosion rate and, therefore, corrosivity information for the environment in question. The use of these techniques applies to anybody who needs to know the corrosivity of an environment, the corrosion rate under a film, or for determination of the onset of paint degradation indicated by infiltration of moisture under the paint which leads to corrosion of the structure.

It is suggested that the LPR sensors be used to determine the corrosion rate under a film. With this corrosion rate information, correct selection of construction materials can be verified or then be made. For example, if the environment is severely corrosive only materials that perform well in that environment should be selected. UFGS 09900 Paints and Coatings should be modified to include the LPR sensors as a quality assurance tool. Under Section 3.13, Inspection and Acceptance the following Note should be added for Division 5 materials.

Note: To determine if the coating is performing as intended, not degrading and allowing moisture to infiltrate under the coating, under-film LPR sensors can be installed during the coating process. These sensors provide instantaneous corrosion rate data from under the coating facilitating early detection of coating problems so corrections can be made in a timely manner before failure. These sensors are especially recommended for use on critical structures that are remote and difficult to physically monitor. They should be installed according to manufacturer's guidelines and specifications.

Appendix A: Report on ERDC Lab Testing of Sensors for Determination of Corrosion

SENSORS FOR MEASUREMENT OF CORROSION RATES AND DETECTION OF CORROSION UNDER COATINGS

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ABSTRACT

Corrosion rate measurement can reveal which areas of a structure need immediate maintenance and which ones will need maintenance later, as well as allow an optimal maintenance schedule to be developed. A new stamp-sized corrosion sensor allows measurement of corrosion rates based on well-established LPR (Linear Polarization Resistor) technology, which outputs an exact corrosion rate for the structure on which it is placed. The corrosion rate data can be monitored continuously or stored in a data collection node, to which eight sensors are attached, and downloaded periodically. This sensor technology is being evaluated in the laboratory under various simulated corrosive field conditions. The sensor is being considered for corrosion monitoring applications on structures for mission critical equipment on military installations in severely corrosive environments. Results of laboratory experiments on the sensitivity of the sensor to the onset of corrosion on the substrate and projections for its applicability in the field will be discussed.

INTRODUCTION

Innovative remote sensors can provide data on corrosion status at various locations of mission-critical metal structures. The sensors can be applied to surfaces of mission-critical steel structures, and will respond to intru-

sion of moisture, which causes decreased electrical resistance as they are affected by changes in the local corrosive environment. Corrosion rates can be predicted from the shifts in polarization resistance. Increasing corrosion rates signal the need for corrective action, such as removal of corrosion, and re-coating of the structure. The sensor to be employed is built on well-established Linear Polarization Resistor (LPR) technology and is intended to output an exact corrosion rate for the structure on which it is placed. The sensor can be placed onto a structure that is stripped down to bare metal and then recoated, or on top of existing coatings that need to be over-coated. Based on this data, it can then be determined at what rate these surfaces are corroding.

Figure 1 shows the sensor at a magnification of 2X, comprised of interdigitated steel fingers on top of a polyimide support film. Starting with the untested but electrically shorted, sensor (No. 3), a typical plan view is presented as Figure II where three different sets of stripes can be seen, the gray areas being the top surfaces of the sensor, interdigitated steel 'fingers' (F), and the yellow-brown areas being the exposed top surface of the adhesive/polyimide support polymer (P). The width of the 'fingers is quite close to that stated by the supplier, namely the narrower 'active' finger being 145 μm (6 mils) wide and the counter/reference finger width being 460 μm (18 mils). The upper plane separation between the fingers ranges from 170 to 185 μm (6.5 to 7 mils). The exposed polyimide widths ranged from 65 to 75 μm.

EXPERIMENTAL PROCEDURES

Three uncoated LPR sensors had been previously provided, gratis, by the manufacturer for evaluation using EIS as the principal interrogation technique. Following four wet/dry cycles with the two 'good' sensors, all three were evaluated for the physical appearances of the various surfaces and dimensions of the sensors using an imaging system[2]. Plan and 3-D views, as well as a limited dimensional analysis of 'shorted' No. 3 sensor and the two environmentally characterized (Nos. 1 and 2) resulted in a rethinking regarding the previously held view of the sensor functionality. The comments regarding the physical appearances of the sensors are being made with limited discussions with the supplier and therefore may be modified at a later date.

A preliminary summary report[1] concluded: a) the three sensors yielded quite different Electrochemical Impedance Spectroscopy (EIS) spectra and responses to changes in the relative humidity (RH) of the 'test air', b) one of the sensors (No. 3) exhibited an electrical 'short circuit' response, c) the low frequency impedance values of the remaining two sensors in a dry environment were considerably higher than the previously determined results generated using the LPR measurement and analysis system and d) further experimental testing of the two 'good' sensors was required.

The two 'good', uncoated, sensors were exposed to three levels of relative humidity for normally one week followed by heatless drying by exposure in a closed vessel containing 'molecular sieves'. This drying approach had been previously used to completely dehydrate various engineering polymers without subjecting the polymers to excursions into the glass transition temperature range, thus assuring the polymer(s) remain in the 'as-received' condition. The electrochemical (EC) response to changes from 'dry' to 'wet' and vice versa was found to be quite rapid and suggests a surface water adsorption/desorption process controls the first-day, sensor condition and therefore the EIS data. The subsequent change in EC performance is then a function of water absorption within the polymer as well as the steel finger corrosion processes, then dependent on the level of relative humidity.

The EIS experiments were performed and involved 4 drying/wetting cycles as presented in Table 2. The sensors were positioned approximately 10 cm above the controlling environments. Complete dryness was attained with Type 13X molecular sieves beads. The 33 % RH condition was that over a saturated $MgCl_2 \bullet 6H_2O$ solution[3], 38 – 55 % RH was normal for the lab during the time-frame and the 100% RH condition was via commercially available distilled water.

Two topics are addressed below; the first is the documented surface examination of mainly Sensor #3, which had not been exposed to the cyclic humidity experiments but with some views included from the rusted sensors, Nos. 1 & 2. The second topic is a summary of the EIS testing.

RESULTS AND DISCUSSION

Physical Evaluation

The imaging system used for physical evaluation of the sensor combines digital 'photography' with microscope viewing of a sample positioned on a precisely controlled x,y,z table. After an initial plan view of the sample is recorded, the z-position is incrementally changed several times as defined by the analyst with only the in-focus information stored in the computer. The software then reassembles/overlays all the x-y data resulting in a 3-D 'reconstruction' of the object's 'surface'. This data file (or surface) can subsequently be rotated by the analyst. Section slices can be dimensionally analyzed as well as areas and surface volumes for data of particular interest.

Figure 1 is a schematic of the sensor, comprised of interdigitated steel fingers on top of a polyimide support film. Starting with the untested but electrically shorted, sensor (No. 3), a typical plan view is presented as Figure 2 where three different sets of stripes can be seen, the gray areas being the top surfaces of the sensor, interdigitated steel 'fingers' (F), and the yellow-brown areas being the exposed top surface of the adhesive/polyimide support polymer (P). The width of the 'fingers is quite close to that stated by the supplier, namely the narrower 'active' finger being 145 μm (6 mils) wide and the counter/reference finger width being 460 μm (18 mils). The upper plane separation between the fingers ranges from 170 to 185 μm (6.5 to 7 mils). The exposed polyimide widths ranged from 65 to 75 μm.

The upper surface of the steel fingers is seen to lay above the adhesive/polyimide surface and the steel finger sides are confirmed to be tapered. The image appears to be skewed and with the complete software, this can be corrected and 'made' planer. The demo software can come closer to showing the taper nature of the fingers. Two artifacts are apparent at the top edge of the wider finger and these were retained rather than removed.

The thickness of the steel was determined to be between 55 and 60 μm (2 – 2.1 mils) based on the section thickness profile feature of the imaging software and this value agrees with the thickness of the steel stated by the supplier. The general appearance indicates that the steel fingers are not permanently, significantly imbedded within the polymer. Whether the

moisture absorption/desorption cycling for Sensors 2 & 1 contribute to a detachment of the steel from the polymer is not determined at this point. As the imaging system never "sees" the bottom plane of the polyamide floor, this thickness and any disbondings could not be documented.

In subsequent examinations, additional general features were seen. The upper metal finger surface showed what appeared to be polish or scratch lines running across the finger widths and roughly 6 rust areas were also evident on the counter/reference finger. Again the corrosion was most evident along the tapered sides of the fingers. The dimensional analysis from the plan view(s) is summarized in Table 1.

The appearance of Sensor 1 was somewhat distinct in that the taper sides oxide layer seemed more pronounced and 'organized'/dense. Also the scratch/polish lines seemed to be more pronounced. The upper surface rust was evident and somewhat more spread out than seen with Sensor 2. The finger width dimensions are included in Table 1.

Previously, the supplier had stated that the metallic sensor fingers were imbedded into the polyimide base. As seen in Figure 2, clearly this is not the case. Following that non-destructive evaluation of the thickness of the steel fingers height(s) and width(s), during the subsequent QA/QC visit to the supplier, the sensor fabricator disclosed more of the fabrication process detail. Essentially, an approximately 25 μm thick layer of a high temperature melt adhesive is applied to one side of the 25 μm thick polyimide film. The 50 μm thick metal (in this case AISI 1010 steel shim stock) is then hot pressed onto the adhesive layer. The pattern for the steel fingers etc. is then established by photo engraving and leaching the unwanted metal, rinsing and finally drying the sensor element. Although not discussed, this might be accomplished by starting with a 50 μm thick adhesive layer. Following the metal removal and washing/drying step, it may be possible to re-hot-press the steel fingers, the adhesive then possibly flowing into the acid created channels, with temperature, pressure and time being the controls to stop the process when the adhesive 'just fills' the void.

Thus it appears that the actual configuration of the sensor is not as had previously envisioned. While this does not affect the sensor serving to activate when exposed to corroding conditions, questions as to the amount as well as location of active metal involved in the process do remain. Re-

solving those questions appears to be necessary to fabricate a set of sensors with reasonably close operating characteristics as well as to improve operation in combination with whatever limitations exist within the LPR measurement and analysis system. This should be accomplished by implementing a quality control procedure to insure that the actual configuration of the LPR sensor is in accordance with the original design, i.e., that the fingers of the sensor are embedded in the polyimide film.

EIS and Moisture Cycling of the Sensors

As discussed previously[1], the EIS data from the two uncoated functional sensors were distinct with Sensor #1 having a low frequency impedance limit of approximately $1 \times 10^{12}\ \Omega$ compared to that seen for #2 of $4.2 \times 10^{9}\Omega$. The wetting and drying segments were performed on both sensors within the same test vessel. However, for brevity, as both sensors responded in the same general fashion the discussion will be limited to the 'behavior' of Sensor #2.

The EIS response for a change from dryness to the 33% RH condition is shown as Figure 3a. where the low frequency impedance drop from $3.1 \times 10^{10}\ \Omega$ to $7.3 \times 10^{9}\ \Omega$ is seen to occur within 6 minutes. The impedance magnitude decreased 50% over the following 7 days. The sensor basic capacitance did increase very slightly during the week as expected, the increase attributable to an increase in absorbed water from 0.24 to 0.6 v/o (volume percent). Although the low frequency range of the Bode Magnitude plot might be suggestive of the development of a second time constant, the Phase Angle plot does not support that notion as can be seen in Figure 3b taken at 1 week exposure.

A more dramatic initial (6 minute) drop of impedance during the dried sensor exposure to the lab ambient 53% RH is seen in Figure 4. Here the decrease was from $5.7 \times 10^{10}\ \Omega$ to $2.7 \times 10^{9}\ \Omega$. Again a small increase is observed in the sensor capacitance and attributable to the absorbed water rise from 0.6 v/o to 0.93 v/o. The EIS model also remained as a one time-constant model, this also being verified with the phase shift information.

There were two 100% RH environment exposures made, the first having been presented previously[1]. There, the drop in impedance in 6 minutes exposure decreased from roughly $4 \times 10^{9}\ \Omega$ to $10^{7}\ \Omega$ and the impedance data were "two time-constant" type response. As indicated in Table 2, the

second 100% RH exposure came as Segment 11, the 4th (and last) wet/dry cycle. The impedance data (Figure 5) dropped down to 2 x 10^4 Ω. In addition to seeing 'rust' on about 50% of the bare upper metal finger surfaces and on 90+ % of the finger electrical feeder strips, rust on the finger undersides and distortions to the polyimide indicate that considerably more than the upper metal surface was electrochemically active. Whether this additional corrosion "is" the cause of the 2nd time constant remains to be demonstrated.

The one week exposure, impedance data from the uncoated Sensor #2 are summarized as a function of the test RH as Figure 6. Included in the figure are two limit lines showing the current operating range for the LPR measurement and analysis system. The limits assume that the LPR measurements correspond to the low frequency EIS values, due to the relatively slow speed at which the LPR measurements are taken. The small decrease of the high impedance value of the uncoated steel sensor exposed to indoor exposures to between "0" and 50% RH is in agreement with many previous atmospheric corrosion studies and common experience. For example, detergent washed, towel dried, carbon steel knives remain rustless in conventional kitchens for very long periods of time.

In Mattsson's classical review[4] which covered the basics regarding atmospheric corrosion, he notes that (water) "adsorption occurs above a certain relative humidity, called the critical relative humidity." He gives no specific value for the 'critical RH" but does note that the amount of water that does absorb increases by 100 fold from that point to 100% RH. The ensuing problems that occur outdoors following water absorption are discussed for the 4 common metals (steel, zinc, copper and aluminum). Considerable additional detail regarding the atmospheric corrosion mechanism(s) for iron and steel are provided by Graedel and Frankenthal[5]. They repeat Mattsson's comment regarding a critical level of RH and add that at 60% RH, an equivalent of two monolayers are on an iron/steel surface, but much in clusters rather than as a uniform layer.

Using the (then) newly available quartz microbalance, which can detect as low as approximately 1/3 of a water monolayer adsorbing onto a gold surfaced quartz crystal, Dante and Kelly[6] present water adsorption data. Starting from 4 water 'monolayers' on gold at 15% RH, the water thickens to 10 'monolayers' at 50% RH and approximately 43 'monolayers' at 85% RH. For gold, which does not react at room temperature under normal

conditions, the adsorption and desorption steps were quite rapid and reproducible, this being seen here with the uncoated steel sensor. Roughly 70 % of the crystal response occurred within 5 minutes after a step from 15% to 85% RH or vice versa. Lee and Staehle[7] repeated the gold/quartz microbalance study, evaluating the effects of RH in the experimental temperature range from 7 to 90 C. Their results were similar to the Dante results with, however, the significant increase in absorbed water occurring more towards the 70% RH level. Their data also show the desorption rate to be about 3 times faster than the adsorption rate. The effort was expanded to include iron[8] as well as copper and nickel. The complexities of having a surface (Fe) that can electro-oxidize without oxygen present and the influence of the oxide film(s) on the adsorption characteristics are presented. Their data suggest that the least amount of water was adsorbed on the iron surface, although the applied surface roughness 'correction' may not have been as rigorous as one would like.

The response of the LPR sensor is consistent with these results, as it exhibits a slow decrease in impedance magnitude with increasing RH and then a much more rapid decrease in impedance magnitude as the RH (and thus the adsorbed moisture) increases beyond 50% upwards to 100%.

Sensors on Glass Plates

Painted Sensor Drying. Four linear polarization resistance sensors from the supplier were adhered to two glass plates by epoxy 5 cm (2 in.) from each other. Two of these linear polarization resistance sensors were then coated with two coats of Sherwin Williams B73 W111/V100 paint and allowed to dry. Two similar sensors were coated with three coats of the same paint and also allowed to dry. Using the LPR measurement and analysis system from the supplier, corrosion rates were monitored over the course of three weeks along with relative ambient humidity in the laboratory space. This three-week period began with painting the sensors with the first coat of paint, followed by a second coat a week later, and a final coat of paint was applied to the sensors in the third week. Measurements during the drying time of all sensors appeared be above the upper limit of the LPR measurement and analysis system. All data points from every sensor registered at 7.5×10^7 ohms.

Humidity Exposure. The four sensors attached to two glass plates were then suspended 10 cm (4 in.) over an enclosed trough of water while readings were taken by the LPR measurement and analysis system. After two weeks of measurement, a scratch was cut 0.84 cm (0.33 in.) away from one sensor and 4.22cm (1.66 in.) away from the other on each plate (See Fig 7). The sensors were then placed back over the water bath for two more weeks. Measurements were taken during this time. Measurements were again at a consistent maximum of 7.5 $X10^7$ ohms even with the consistent 100% humidity. Scribing the paint did not make any difference in any readings of the sensors.

UV/Salt Fog Exposure. The remaining LPR sensors were adhered by epoxy to specifically designed glass slides the correct dimensions to insert into UV/Salt Fog ASTM D 5894 Test. Over the course of 12 weeks the sensors will be monitored every 10 minutes by LPR measurement and analysis system. This experiment is still currently underway. Due to the harsh nature of the test and its duration, measurable results are expected.

Sensors on Glass Plates UV/CON Exposure. Finally, three LPR sensors were adhered by epoxy to specifically designed glass slides the correct dimensions to insert into UV/CON ASTM D 4587-05 Test Standard Practice for Fluorescent UV-Condensation Exposures of Paint and Related Coatings. Coated sensors were tested over the course of 12 weeks the corrosion rates were recorded every 10 minutes. Figure 8 shows some of the panels with the sensors under the coating. The UV/CON exposure simulated corrosion rate under coating due to coating degradation for cycles of 4 hr UV @ 60 deg F followed by 4 hr Condensation @ 40 deg F.

The results are shown in Figure 9a, 9b, and 9c. It is seen that the corrosion rate follows the wet and dry cycles for all three LPR sensors, consistently through out the 12 weeks, with a slight lag at the beginning of both the wet and dry cycles in the first week, but tracking the onset of wet and dry cycles without delay by the sixth week. .It is also seen that the maximum corrosion rate decreased consistently throughout the test. The interpretation of these somewhat surprising results were that the paint had performed well as a corrosion barrier and was in the process of “drying out” as it cured over time and UV exposure. Note that the corrosion rate, which initially showed initial corrosion rates at 10^{-3} mm/yr had stabilized to 8 X 10^{-5} mm/yr by the twelfth week of UV/condensation exposure. Laboratory tests are continuing to determine if the sensors will show

higher corrosion rates eventually if the paint is subjected to more cycles of UV. Also, similar LPR sensors have recently been installed under water-born epoxy paint on a metal roof at an Army Installation in Okinawa, Japan, in a severely corrosive coastal environment located within 1 km of the ocean. The corrosion rate data will be measured at 15 minute intervals and transmitted remotely to our laboratories to determine long term field performance of the sensors over the next year.

CONCLUSIONS

The uncoated steel (LPR) corrosion sensor shows an expected low frequency impedance response as a function of exposure to the RH. The high impedances seen at low RH values via the EIS system are considerable higher than the measuring capability of the LPR measurement and analysis system. At the high humidity ranges, the LPR measurement and analysis system can measure LPR values as low as $2.5 \times 10^4\ \Omega$, which for a steel sensor, may be approaching the higher corrosion current measuring limits. While this may be unsatisfactory to some who prefer more complete knowledge regarding the state of steel in a potentially corroding environment, the fact that the LPR measurement and analysis system provides "safe" vs. "unsafe" condition 'measurement' may be sufficient. This limited study also showed two additional problems. The widely different electrochemical response of these three manufactured sensors is obviously a QA/QC problem. An independent evaluation of a set of at least 8 sensors is warranted to see the response spread of the current manufacturing variances. And although not discussed, but perhaps observable from the drop in impedance via the EIS data and post test visual examinations, the sensor deterioration during or following the fourth moisture adsorb/desorb cycle may be indicative of a disbonding of the steel 'fingers' from the adhesive. This potential problem may be resolved if the sensor manufacturer can 'truly' imbed the fingers within the polymer layer.

Conclusions for the first two experiments, viz., EIS/moisture cycling and humidity exposure are that there was either no degradation of the sensor due to corrosion or, more likely, the upper limit on the LPR measurement and analysis system is set too low.

From the UV/CON experiments, it was concluded that the coated glass plated subjected to UV/CON to simulate measure of corrosion rate under coating due to coating degradation at 4 hr UV @ 60 deg F/ 4 hr Condensa-

tion @ 40 deg F showed initial corrosion rates at 10-3 mm/yr. decreasing over a period of 6 weeks and then stabilizing to 8 X 10-5 mm/yr. Corrosion rates were consistent with UV/CON test cycles: increasing with condensation (moisture laden environment) and decreasing with UV exposure. The investigation is on-going to determine if this is due to the curing of the paint. These LPR sensors are now being tested in the field, and are being interfaced with a system which will allow transmission of data via the internet using satellite uplink/downlink.

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TABLE 1

Width Dimensions of Steel Fingers and Exposed Adhesive/Polyimide (microns; (mils))

	Polyimide 'floor'	Working Finger	Polyimide 'floor'	Counter/Ref Finger	Polyimide 'floor'	Working Finger
Sensor 3*	75 (3)	145 (6)	75 (3)	460 (18)	75 (3)	NA "
(From Excel Software)	73	137	68	434	NM	NM
Sensor 2	NA "	NA "	NA "	425 (16.5)	70 (2.5)	120 (4.5)
Sensor 1	75 (3)	115 (4.5)	80 (3)	415 (16)	70 (2.5)	NA "

NA = Not Available in viewed segment
NM = Not measured
* no scale bar available; values averaged from 'finger' specs.

TABLE 2

Chronology of Sensors Runs

Segment #	Dry(D)/Wet(W)	RH(%)	Dates
1	-	~30	3/9 – 3/10
2	-	~30	3/10 – 3/11
3	D	0	3/11 – 3/23
4	W	100	3/23 – 4/18
5	D	38	4/18 – 4/28
6	D	0	4/28 – 6/5
7	W	53	6/5 – 6/13
8	D	0	6/13 – 7/12
9	W	33	7/12 – 7/19
10	D	0	7/19 – 7/26
11	W	100	7/27 - 8/3
12	D	0	8/3 - 8/4

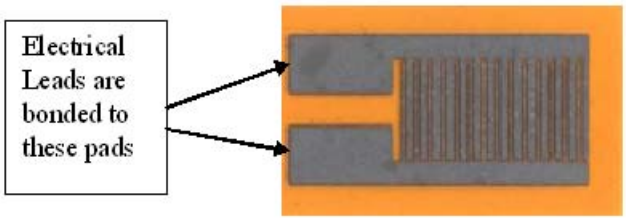


FIGURE 1 - Linear polarization sensor on polyimide film with inter-digitated fingers (2X).

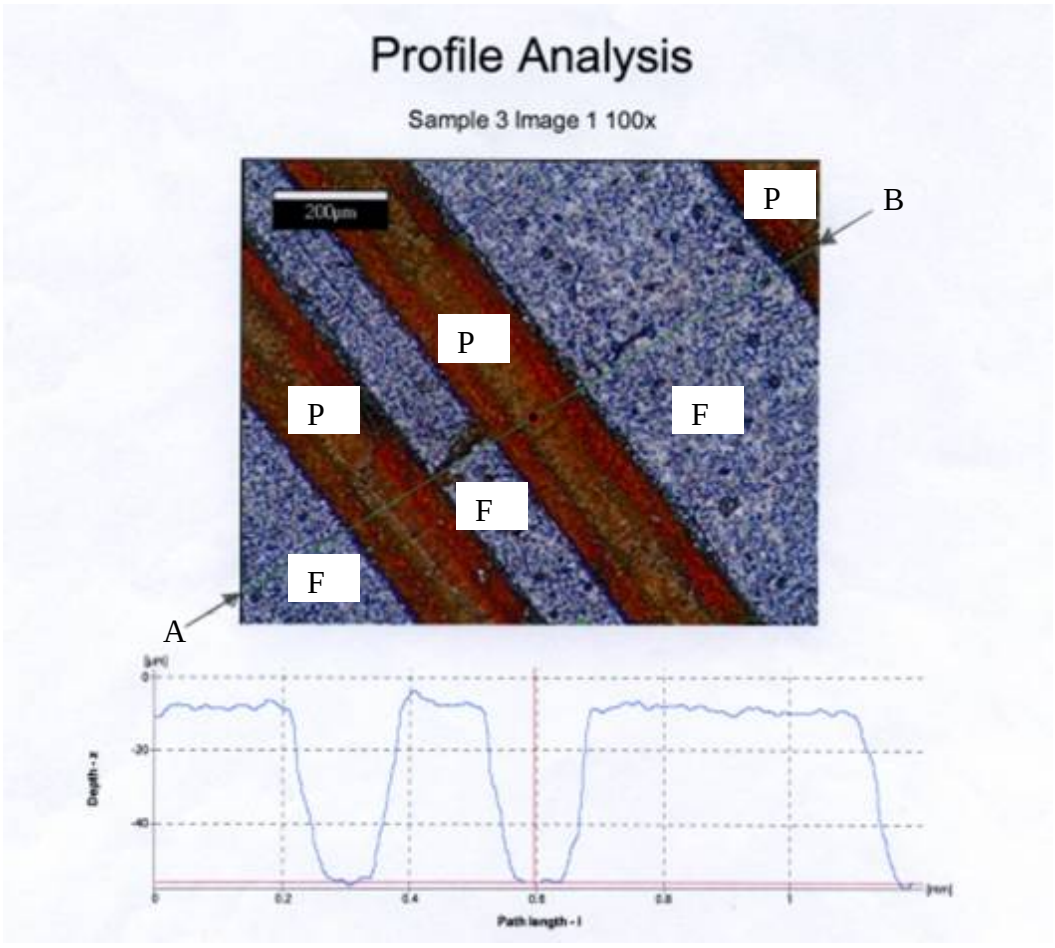


FIGURE 2 - Plan view of electrically shorted, sensor (No. 3), a typical plan view and profile along line AB (F- top surfaces of the sensor, interdigitated steel 'fingers'; P- exposed top surface of the polyimide support polymer).

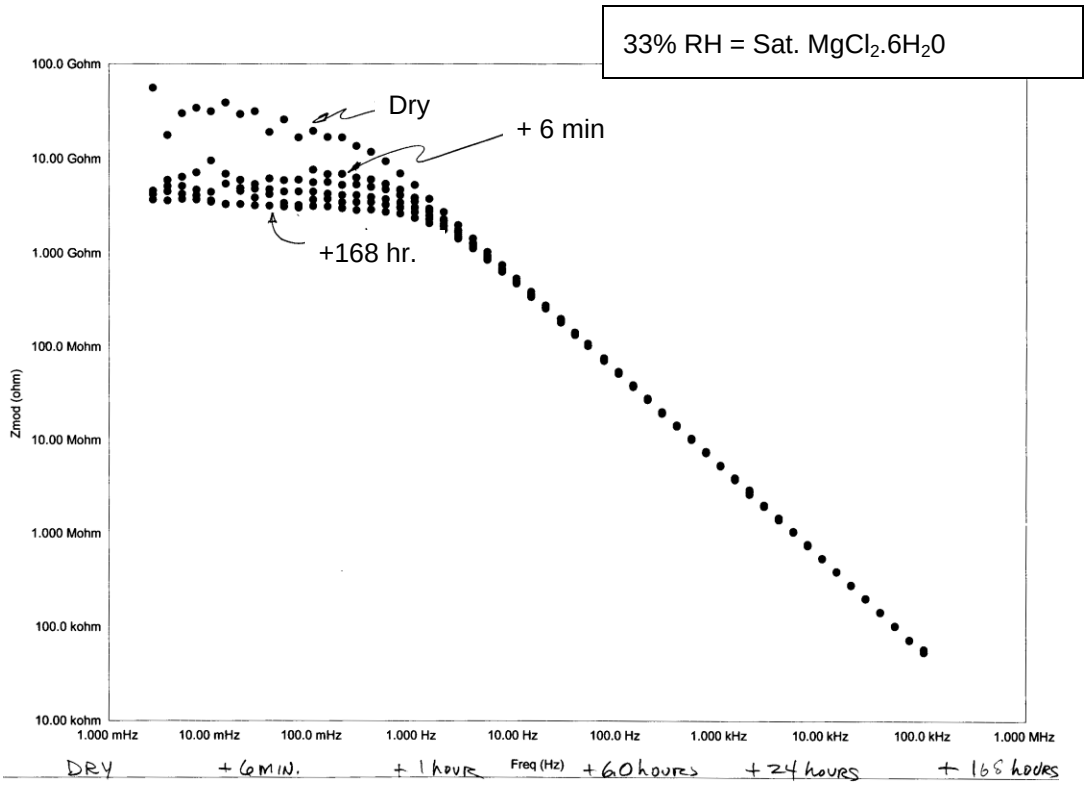


FIGURE 3a - Sensor No. 2, EIS response(s), segment 9, 33% RH.

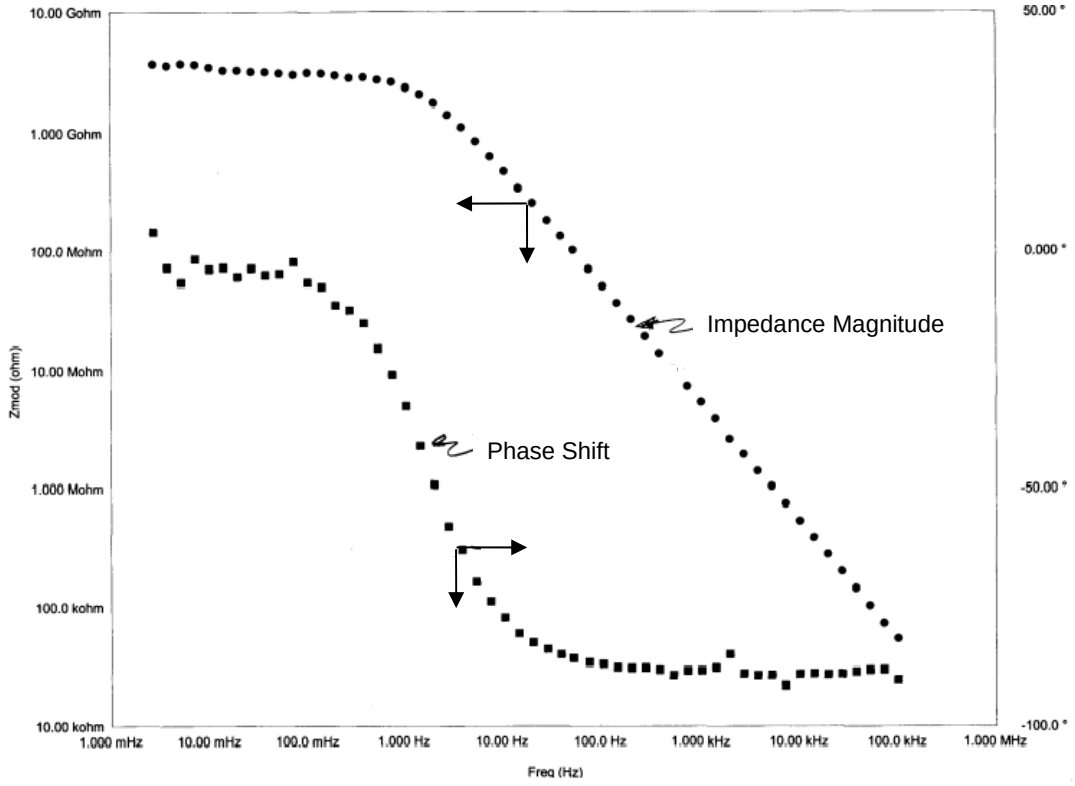


FIGURE 3b - Sensor No. 2, EIS of 33% RH at 168 hours of exposure.

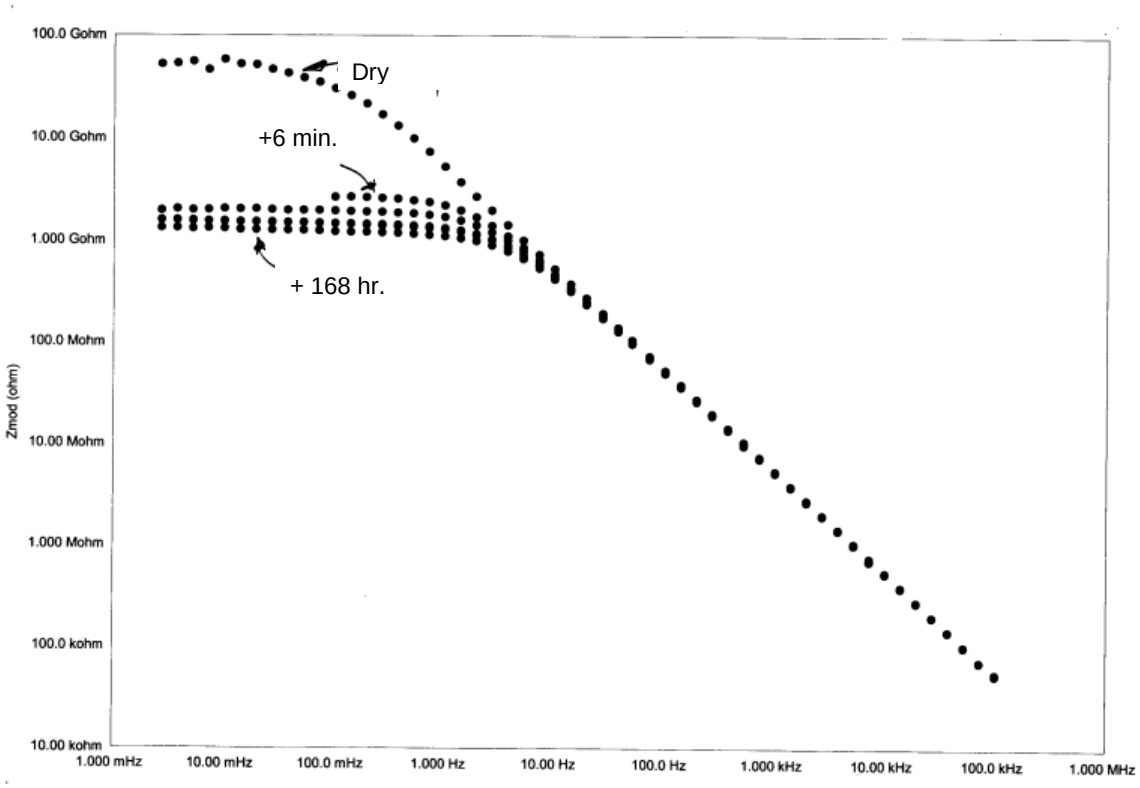


FIGURE 4 - EIS response (s), segment 7, 53% RH.

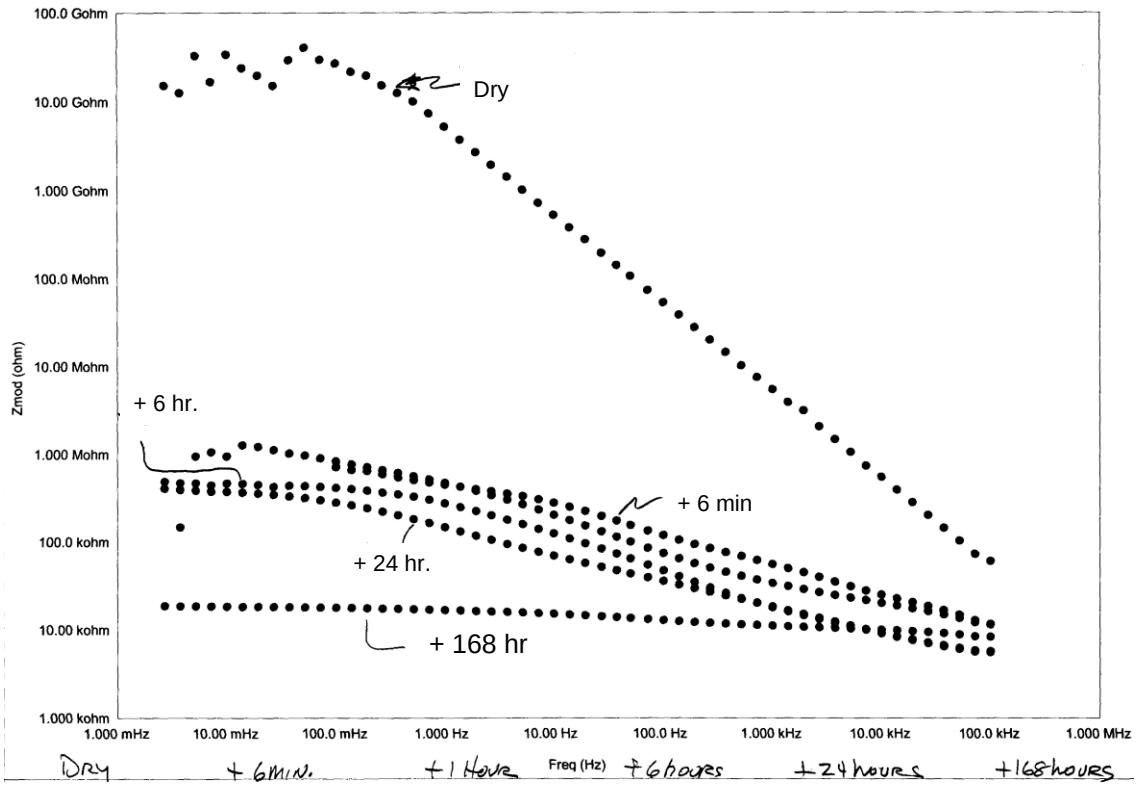


FIGURE 5 - Sensor No.2, EIS response(s), segment 11, 100% RH.

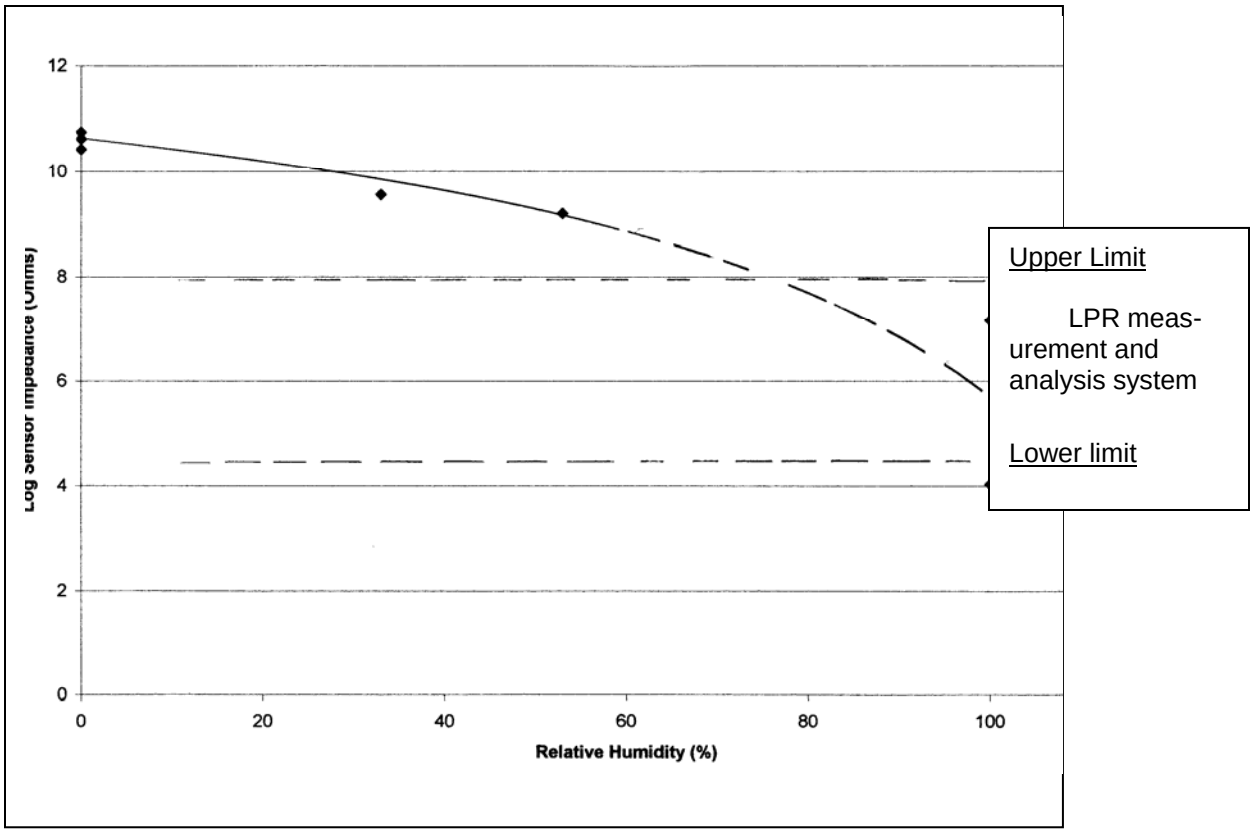


FIGURE 6 - Log sensor impedance vs. relative humidity.

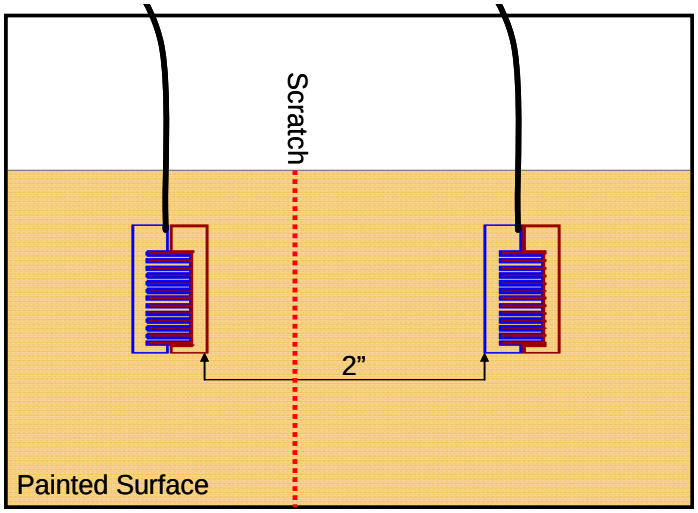


FIGURE 7 - Sensor set up on painted glass for 100% humidity and scribe testing.



FIGURE 8 - Test panels consisting of water-borne epoxy coating painted over LPR sensors.

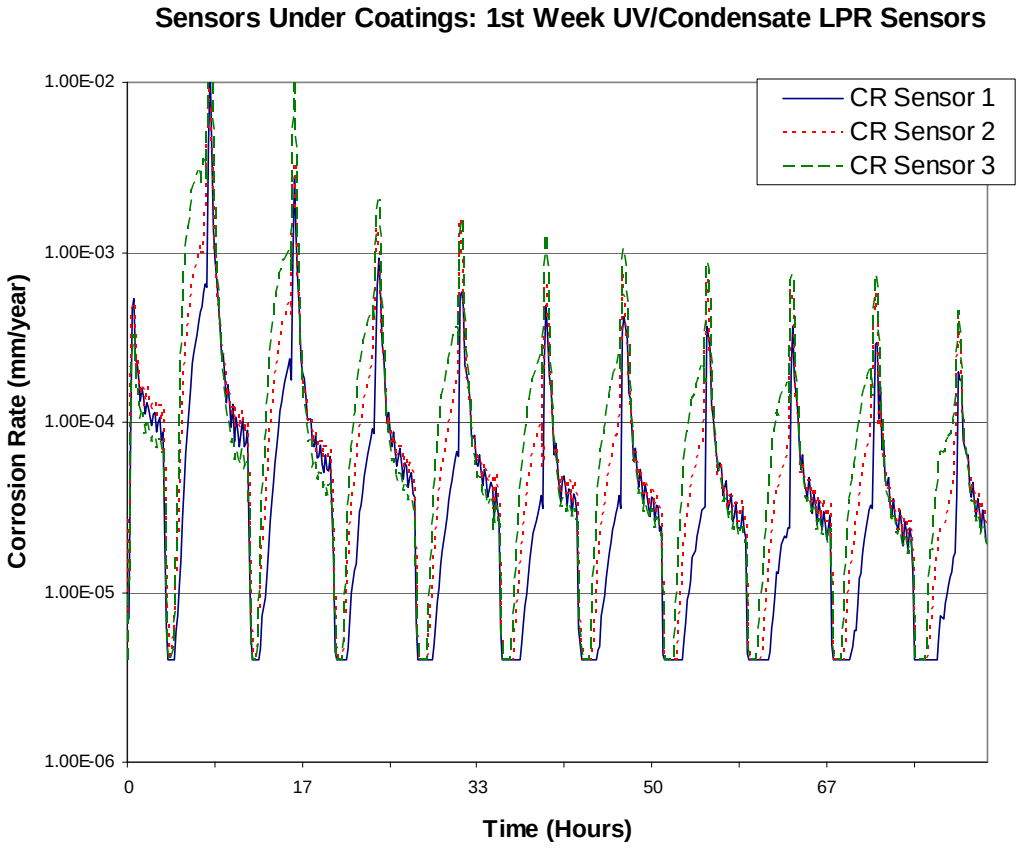


FIGURE 9a - Corrosion Rate vs. Time for LPR sensor under paint subjected to UV/CON Exposure for 1 Week.

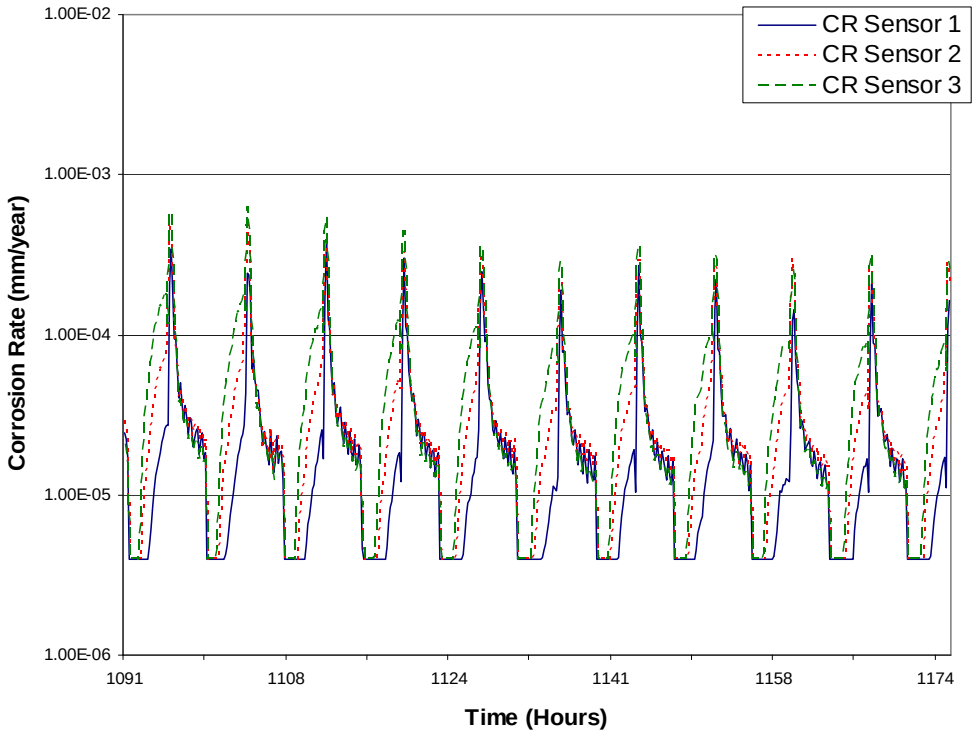


FIGURE 9b - Corrosion Rate vs. Time for LPR sensor under paint subjected to UV/CON Exposure during Week 6.

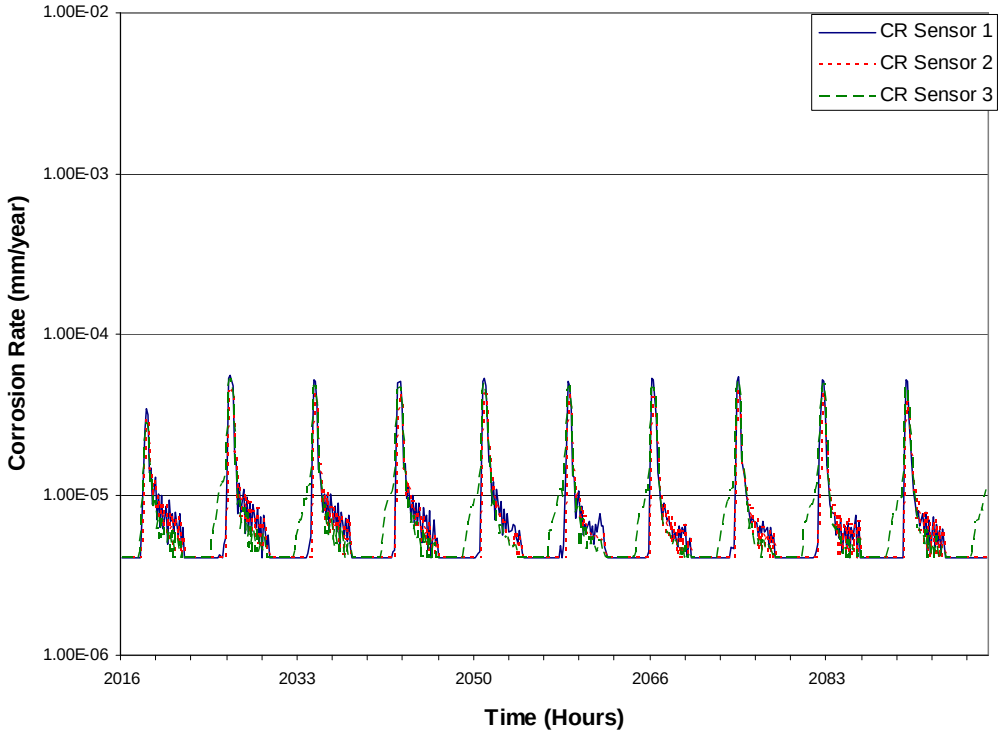


FIGURE 9c - Corrosion Rate vs. Time for LPR sensor under paint subjected to UV/CON Exposure during Week 12.

Appendix B: Description of LPR Sensors and Testing in the Contractor's Laboratory

Analatom micro-machined LPR corrosion sensor

The micro-machined LPR corrosion sensor is built on well-established linear polarization resistor (LPR) technology and it is designed to output an exact corrosion rate for the structure on which it is placed. The device is fabricated using semiconductor production techniques that allow for a high quality product that is low cost and robust. The sensors are available for most metals.

The sensor shown in Figure 1 can be placed on bare metal and all standard coatings applied. Typical applications are:

- Aerospace
- Bridges
- Pipeline
- Automotive
- Air Conditioning systems.



Figure 1. Typical corrosion on a 1010 steel LPR

Sensors are connected to a central data node, shown in Figure 2, that processes the sensors output, stores the data and communicates serially with a PC. The node is also capable of recording data from most standard off the shelf sensors. Nodes can be battery powered and have a typical life of 5 years between battery changes when used for corrosion monitoring. Solar and bus powered systems are also available.



Figure 2. An unpackaged node connected to four sensors

The electrochemical technique commonly referred to as Linear Polarization Resistance allows for measurement of rates of corrosion directly, in real time. The polarization resistance of the material is defined as the slope of the potential-current curve at the free corrosion potential. The rate of corrosion is determined by the change in the properties of the metal-environment interface due to reactions taking place on the metal surface, which influence the corrosion current density. How the corrosion rate is calculated is detailed in Appendix H.

Micro LPR corrosion monitor technical specifications

Table 1 gives the technical specifications for the Analatom LPR corrosion sensor system.

Table 1. Analatom Micro Machined LPR Corrosion Sensor Technical Specifications

Spec	Value	Units
Temperature		
min	-40	°C
max	85	°C
Voltage		
min	2.7	volts
max	3.6	volts
Current Drain		
data download (RS-232)	3	mA
data measurement	1	mA
between measurements	8	µA
with 802.11b module	500	mA

Spec	Value	Units
data download (ZigBee)	45	mA
Data Transfer		
download speed (RS-232)	4,800	baud
download speed (ZigBee)	115,200	baud
Data Storage		
size	55,000	bytes
number of measurements	1,700	---
External Sensors		
extra A/D channels for external off-the-shelf sensors	4	---
Detectable Corrosion Rates (304 Steel)		
min	0.0001	mm/year
max	10	mm/year

Data-gathering electronics, software, and GUI

Figure 3 shows pictures and illustrations of the data gathering electronics, how the sensors are linked into the system, a software output example, and a picture depicting the relative size of the LPR sensor.

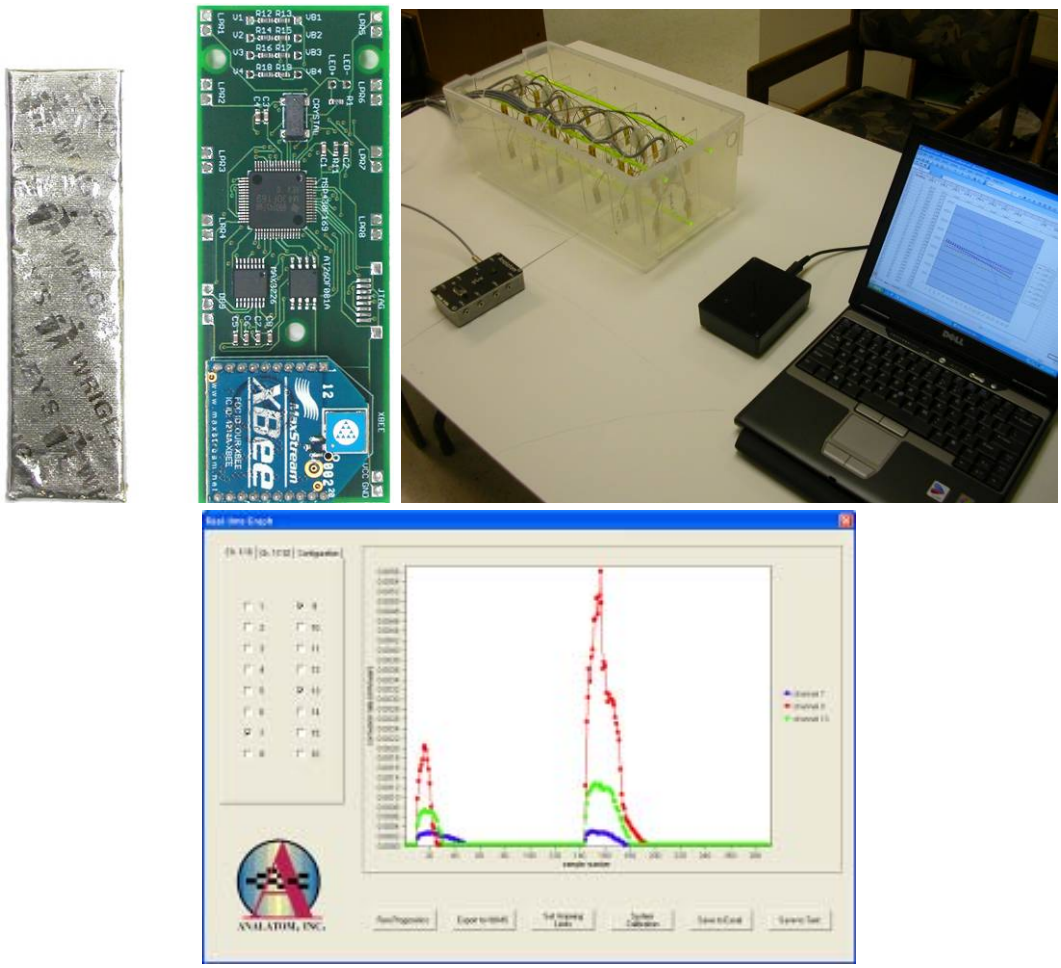


Figure 3. Illustration of data-gathering electronics, software, and GUI.

Laboratory tests representing Torii island environment

In order to evaluate the paint that was used for the sensor node test and to ensure that the LPR corrosion sensors were able to take data while underneath the paint coating, laboratory tests were conducted to represent conditions that would exist when the sensors were placed in the field.

Tests were performed to evaluate the compatibility of the LPR corrosion sensors and the Sherwin Williams epoxy paint and primer that were used as a test coating at Torii Station. Four metal panels of identical size, two made of aluminum and two of 1010 steel, were prepared. On each metal panel, two square areas that were 4 inches on a side were taped off, and a sensor attached to the middle of each square. Each panel had two sensors, for a total of eight sensors. Following the directions for the primer, the catalyst was mixed with the epoxy primer, and each square area with sensor was painted over. The primer was then allowed to cure for 24 hours.

After curing, each square test area on the panel was then painted over with the epoxy-based paint, using a wet-coating thickness gauge to make sure that the coating was even and within the specifications that came with the paint. The paint was then allowed to cure for 24 hours.

After the paint had cured, one steel panel and one aluminum panel each were placed into two Rubbermaid containers, one filled with 1.5 inches of salt water (standard concentration 3.5% NaCl) and the other with 1.5 inches of tap water. Lids were then placed on the containers, and sealed so that no moisture could escape. The sensors were then connected to the sensor node, and data recording was initiated. Figure 4 depicts this test setup.

For the first 3 days, the sensor node collected data every minute; afterwards, the data collection frequency was reduced to once every hour. Data logging was then done for approximately 1 month.



Figure 4. Lab setup used to simulate conditions at Okinawa.

Within a minute of placing the test panels in a humid environment, as shown in Figures 5 and 6, one sensor in each of the test chambers immediately started showing detectable corrosion and, over the next 9 hours, all eight sensors started indicating corrosion. As the moisture slowly penetrated through the coating, the reported corrosion rates continued to rise at a fast rate over the next 24 hours, at which point the corrosion rates leveled off to some degree. The corrosion rates then cycled up and down over the next 3 days with a slight trend upward, presumably due to the rise and fall of temperature between night and day in the laboratory, and perhaps from the continued curing of the paint.

This test was primarily done to see if the LPR corrosion sensor would be able to detect corrosion underneath the epoxy paint that was going to be applied on top of the sensors at Torii Station. Therefore, no attempt was made to keep either temperature or humidity at a constant value.

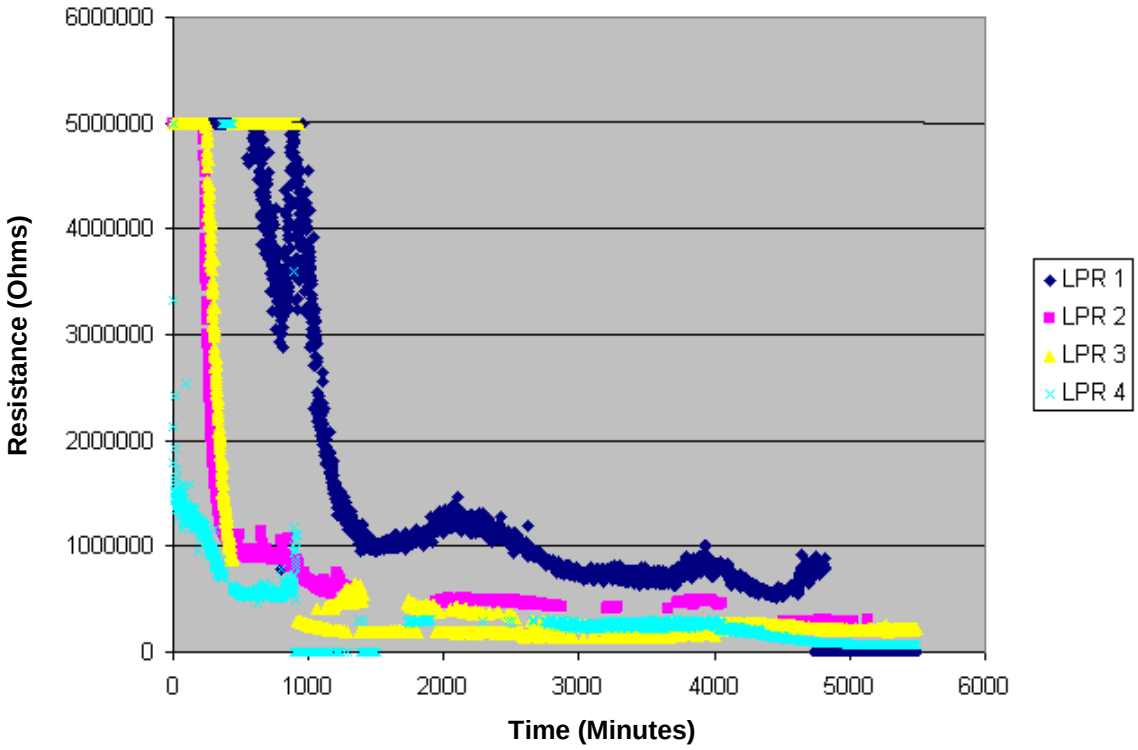


Figure 5. LPR corrosion sensor in tap water humid environment.

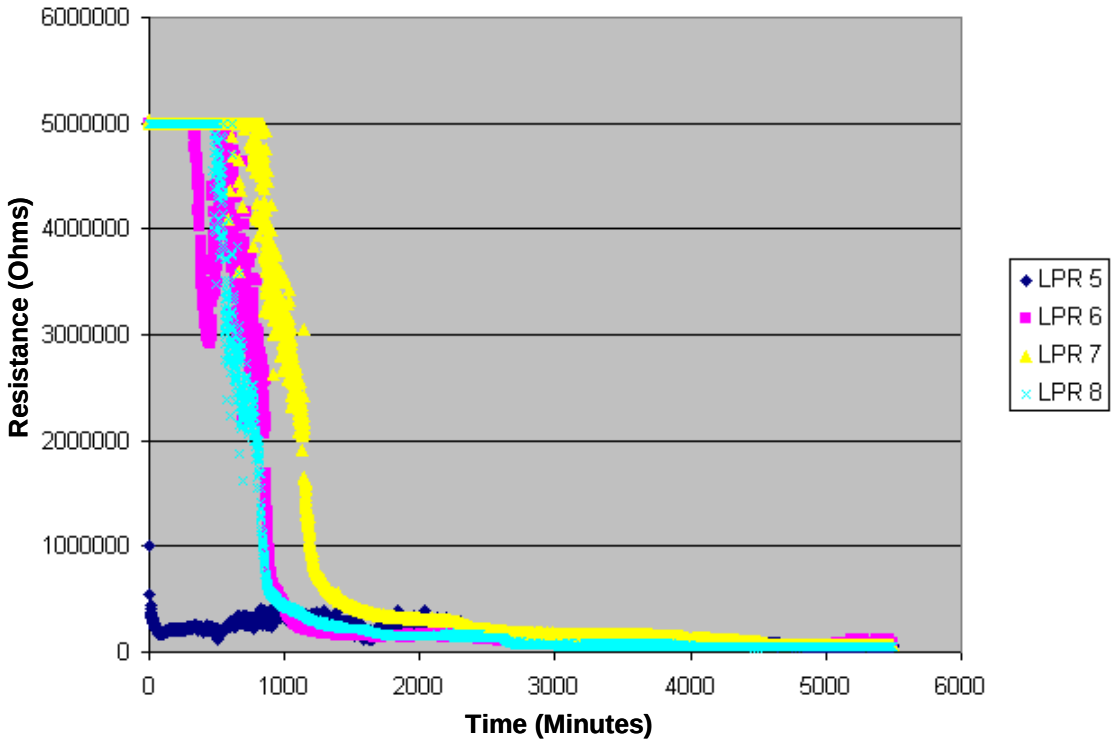


Figure 6. LPR corrosion sensor in salt water humid environment.

Appendix C: Redesign of Waterproofing Enclosures for System Components

Installation of the electronics for the sensors in this humid environment required special waterproof packaging to make the system more robust and waterproof. In order to meet these requirements, the components used were carefully chosen. The electronics enclosure shown in Figure 1 is a Pactec OD45, which uses a rubber gasket to provide a waterproof seal. The connectors used are Binder 620 series and are shown in Figure 2. They where chosen for both their IP-67 rating (Ingress Protection rating, a measure of water tightness), and their small size allows them to fit in the Pactec enclosure. In order to securely mount the printed circuit board (PCB) without drilling holes in the enclosure (the holes would compromise the water tightness of the enclosure), a carrier PCB was designed. This carrier board had holes that aligned with both the Pactec enclosure and the PCB of the sensor node. The sensor node PCB is attached to the carrier PCB, which in turn is connected to the Pactec enclosure.

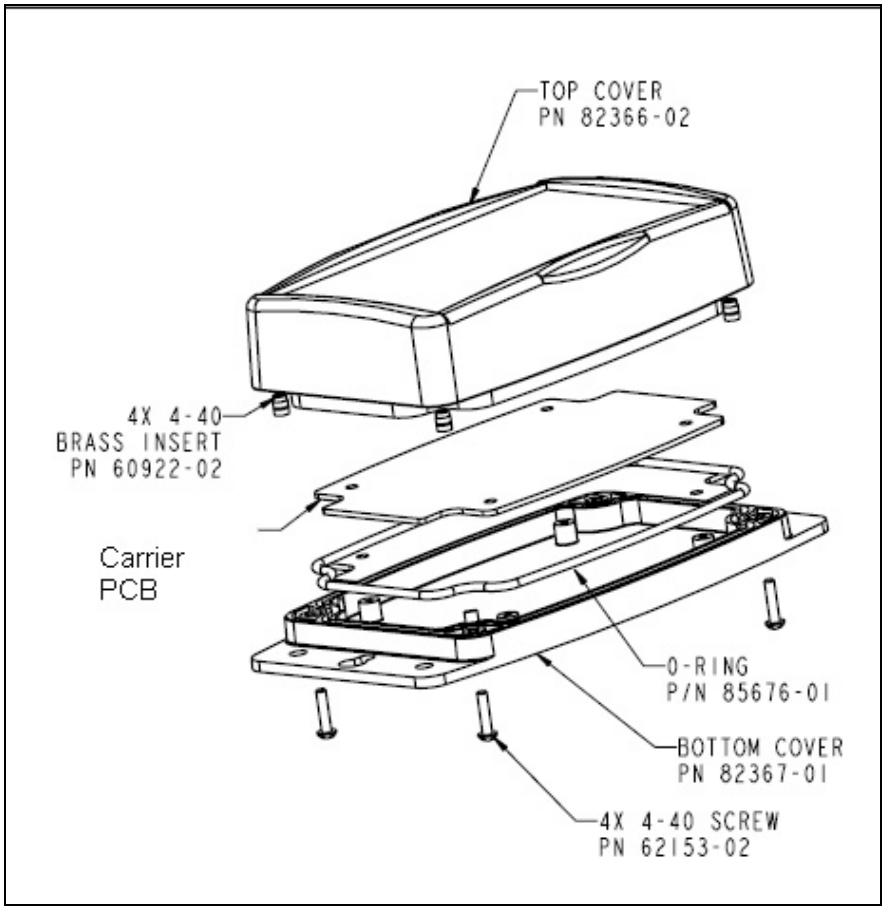


Figure 1. Waterproof Pactec OD 45 LPR System Electronics Node Enclosure



Figure 2. Binder 620 Series Connectors

The second enclosure involved is used to house the serial communications cable that was attached to the sensor node on the roof. However, the second enclosure, which is shown in Figure 3, is mounted on the side of the building so that a technician can periodically download data collected by the sensor node without having to climb to the roof. This enclosure also had to be waterproof, with a waterproof RS-232 serial connector.



Figure 3. Waterproof communications cable enclosure.

The previous enclosure, shown in Figure 4a, was not waterproof. The screw holes, electrical connector holes, and back plate were not watertight. The new box introduced in this project, shown in Figure 4b, uses a waterproof gasket, and the screws are outside of sealing area, making it a reliable waterproof case.

a)



b)

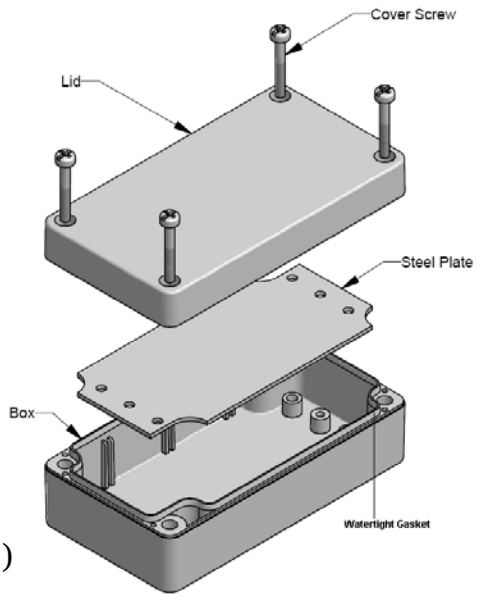


Figure 4. a) Current enclosure electronics, b) Waterproof enclosure electronics for this project

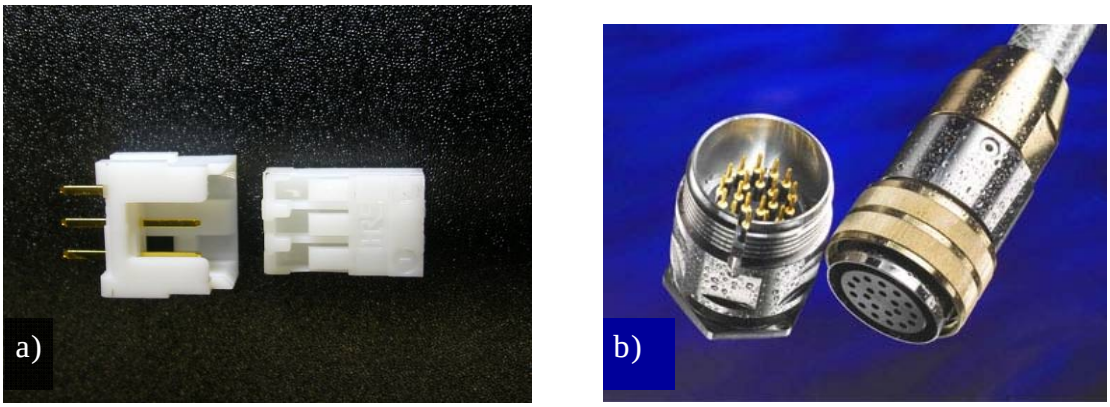


Figure 5. a) Current connector and b) Connector for this project.

The previous connector, shown in Figure 5a, was not sealed at all and also did not seal to the enclosure. The previous connector was also susceptible to accidental unplugging. The new connector, shown in Figure 5b, is waterproof and the connection through the box is sealed as well. The new connector is also stronger physically and is more resistant to accidental disconnection. All these changes make for a very tough and reliable corrosion monitoring system. Figure 5b is only an example; it has many pins whereas we only use a 3-pin model.

Appendix D: Corrosion Monitoring Techniques

Introduction to Corrosion Monitoring

What is Corrosion Monitoring?

The field of corrosion measurement, control, and prevention covers a very broad spectrum of technical activities. Within the sphere of corrosion control and prevention, there are technical options such as cathodic and anodic protection, materials selection, chemical dosing and the application of internal and external coatings. Corrosion measurement employs a variety of techniques to determine how corrosive the environment is and at what rate metal loss is being experienced. Corrosion measurement is the quantitative method by which the effectiveness of corrosion control and prevention techniques can be evaluated and provides the feedback to enable corrosion control and prevention methods to be optimized.

A wide variety of corrosion measurement techniques exists, including:

Non Destructive Testing
- Ultrasonic testing
- Radiography
- Thermography
- Eddy current/magnetic flux
- Intelligent pigs

Operational Data
- pH
- Flow rate (velocity)
- Pressure
- Temperature

Corrosion Monitoring
- Weight loss coupons
- Electrical resistance
- Linear polarization
- Hydrogen penetration
- Galvanic current

Analytical Chemistry
- pH measurement
- Dissolved gas (O_2, CO_2, H_2S)
- Metal ion count (Fe^{2+}, Fe^{3+})
- Microbiological analysis

Fluid Electrochemistry
- Potential measurement
- Potentiostatic measurements
- Potentiodynamic measurements
- A.C. impedance

Some corrosion measurement techniques can be used on-line, constantly exposed to the process stream, while others provide off-line measurement, such as that determined in a laboratory analysis. Some techniques give a direct measure of metal loss or corrosion rate, while others are used to infer that a corrosive environment may exist.

Corrosion monitoring is the practice of measuring the corrosivity of process stream conditions by the use of "probes" which are inserted into the process stream and which are continuously exposed to the process stream condition.

Corrosion monitoring "probes" can be mechanical, electrical, or electrochemical devices.

Corrosion monitoring techniques alone provide direct and online measurement of metal loss/corrosion rate in industrial process systems.

Typically, a corrosion measurement, inspection and maintenance program used in any industrial facility will incorporate the measurement elements provided by the four combinations of on-line/off-line, direct/indirect measurements.

- Corrosion Monitoring Direct, On-line
- Non Destructive Testing Direct, Off-line
- Analytical Chemistry Indirect, Off-line
- Operational Data Indirect, On-line

In a well controlled and coordinated program, data from each source will be used to draw meaningful conclusions about the operational corrosion rates with the process system and how these are most effectively minimized.

The Need for Corrosion Monitoring

The rate of corrosion dictates how long any process equipment can be usefully and safely operated. The measurement of corrosion and the action to remedy high corrosion rates permits the most cost effective plant operation to be achieved while reducing the life-cycle costs associated with the operation.

Corrosion monitoring techniques can help in several ways:

(1) by providing an early warning that damaging process conditions exist which may result in a corrosion-induced failure.

(2) by studying the correlation of changes in process parameters and their effect on system corrosivity.

(3) by diagnosing a particular corrosion problem, identifying its cause and the rate controlling parameters, such as pressure, temperature, pH, flow rate, etc.

(4) by evaluating the effectiveness of a corrosion control/prevention technique such as chemical inhibition and the determination of optimal applications.

(5) by providing management information relating to the maintenance requirements and ongoing condition of plant.

Corrosion Monitoring Techniques

A large number of corrosion monitoring techniques exist. The following list details the most common techniques which are used in industrial applications:

- Corrosion Coupons (weight loss measurements)
- Electrical Resistance (ER)
- Linear Polarization Resistance (LPR)
- Galvanic (ZRA)
- Hydrogen Penetration
- Microbial
- Sand/Erosion

Other techniques do exist, but almost all require some expert operation, or otherwise are not sufficiently rugged or adaptable to plant applications.

Of the techniques listed above, corrosion coupons, ER, and LPR form the core of industrial corrosion monitoring systems. The four other techniques are normally found in specialized applications which are discussed later.

These corrosion monitoring techniques have been successfully applied and are used in an increasing range of applications because:

- The techniques are easy to understand and implement.
- Equipment reliability has been demonstrated in the field environment over many years of operational application.
- Results are easy to interpret.
- Measuring equipment can be made intrinsically safe for hazardous area operation.
- Users have experienced significant economic benefit through reduced plant down time and plant life extension.

Corrosion Coupons (Weight Loss)

The Weight Loss technique is the best known and simplest of all corrosion monitoring techniques. The method involves exposing a specimen of material (the coupon) to a process environment for a given duration, then removing the specimen for analysis. The basic measurement which is determined from corrosion coupons is weight loss; the weight loss taking place over the period of exposure being expressed as corrosion rate.



The simplicity of the measurement offered by the corrosion coupon is such that the coupon technique forms the baseline method of measurement in many corrosion monitoring programs.

The technique is extremely versatile, since weight loss coupons can be fabricated from any commercially available alloy. Also, using appropriate geometric designs, a wide variety of corrosion phenomena may be studied which includes, but is not limited to:

- Stress-assisted corrosion
- Bimetallic (galvanic) attack
- Differential aeration
- Heat-affected zones

Advantages of weight loss coupons are that:

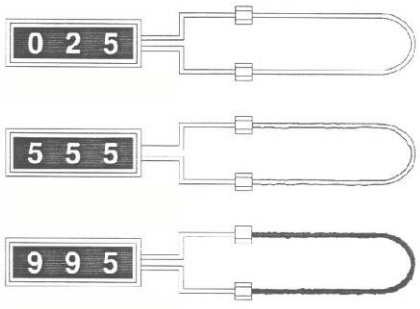
- The technique is applicable to all environments - gases, liquids, solids/particulate flow.
- Visual inspection can be undertaken.
- Corrosion deposits can be observed and analyzed.
- Weight loss can be readily determined and corrosion rate easily calculated.
- Localized corrosion can be identified and measured.
- Inhibitor performance can be easily assessed.

In a typical monitoring program, coupons are exposed for a 90-day duration before being removed for a laboratory analysis. This gives basic corrosion rate measurements at a frequency of four times per year. The weight loss resulting from any single coupon exposure yields the "average" value of corrosion occurring during that exposure. The disadvantage of the coupon technique is that, if a corrosion upset occurs during the period of exposure, the coupon alone will not be able to identify the time of occurrence of the upset, and depending upon the peak value of the upset and its duration, may not even register a statistically significant increased weight loss.

Therefore, coupon monitoring is most useful in environments where corrosion rates do not significantly change over long time periods. However, they can provide a useful correlation with other techniques such as ER and LPR measurements.

Electrical Resistance (ER) Monitoring

ER probes can be thought of as "electronic" corrosion coupons. Like coupons, ER probes provide a basic measurement of metal loss, but unlike coupons, the value of metal loss can be measured at any time, as frequently as required, while the probe is in-situ and permanently exposed to the process stream.

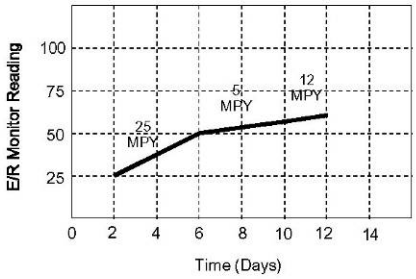


In this diagram, a standard ER instrument is connected to a 40 mil wire loop element which has a useful life of 10 mils. The instrument still reads close to zero because the element is new.

Here the instrument reads around half-scale, indicating that the element has experienced about 5 mils of metal loss or about half of its useful life. The instrument's reading is increasing proportionally with the resistance of the element, which increases as a result of metal loss.

Here the instrument reads almost full scale, indicating that the element has experienced 10 mils of metal loss and requires replacement.

The ER technique measures the change in Ohmic resistance of a corroding metal element exposed to the process stream. The action of corrosion on the surface of the element produces a decrease in its cross-sectional area with a corresponding increase in its electrical resistance. The increase in resistance can be related directly to metal loss and the metal loss as a function of time is by definition the corrosion rate. Although still a time averaged technique, the response time for ER monitoring is far shorter than that for weight loss coupons. The graph below shows typical response times.



ER probes have all the advantages of coupons, plus:

- Direct corrosion rates can be obtained.
- Probe remains installed in-line until operational life has been exhausted.
- They respond quickly to corrosion upsets and can be used to trigger an alarm.

ER probes are available in a variety of element geometries, metallurgies and sensitivities and can be configured for flush mounting such that pigging operations can take place without the necessity to remove probes. The range of sensitivities allows the operator to select the most dynamic response consistent with process requirements.

Linear Polarization Resistance (LPR) Monitoring

The LPR technique is based on complex electro-chemical theory. For purposes of industrial measurement applications it is simplified to a very basic concept. In fundamental terms, a small voltage (or polarization potential) is applied to an electrode in solution. The current needed to maintain a specific voltage shift (typically 10 mV) is directly related to the corrosion on the surface of the electrode in the solution. By measuring the current, a corrosion rate can be derived.



The advantage of the LPR technique is that the measurement of corrosion rate is made instantaneously. This is a more powerful tool than either coupons or ER where the fundamental measurement is metal loss and where some period of exposure is required to determine corrosion rate. The disadvantage to the LPR

technique is that it can only be successfully performed in relatively clean aqueous electrolytic environments. LPR will not work in gases or water/oil emulsions where fouling of the electrodes will prevent measurements being made.

Galvanic Monitoring

The galvanic monitoring technique, also known as Zero Resistance Ammetry (ZRA) is another electrochemical measuring technique. With ZRA probes, two electrodes of dissimilar metals are exposed to the process fluid. When immersed in solution, a natural voltage (potential) difference exits between the electrodes. The current generated due to this potential difference relates to the rate of corrosion which is occurring on the more active of the electrode couple.

Galvanic monitoring is applicable to the following electrode couples:

- Bimetallic corrosion
- Crevice and pitting attack
- Corrosion assisted cracking
- Corrosion by highly oxidizing species
- Weld decay

Galvanic current measurement has found its widest applications in water injection systems where dissolved oxygen concentrations are a primary concern. Oxygen leaking into such systems greatly increases galvanic currents and thus the corrosion rate of steel process components. Galvanic monitoring systems are used to provide an indication that oxygen may be invading injection waters through leaking gaskets or deaeration systems.

Specialized Monitoring

Biological Monitoring

Biological monitoring and analysis generally seeks to identify the presence of Sulphate Reducing Bacteria - SRB's. This is a class of anaerobic bacteria which consume sulphate from the process stream and generate sulphuric acid, a corrosive which attacks production plant materials.



Sand / Erosion Monitoring

These are devices which are designed to measure erosion in a flowing system. They find wide application in oil/gas production systems where particulate matter is present.

Hydrogen Penetration Monitoring

In acidic process environments, hydrogen is a by-product of the corrosion reaction. Hydrogen generated in such a reaction can be absorbed by steel particularly when traces of sulphide or cyanide are present. This may lead to hydrogen induced failure by one or more of several mechanisms. The concept of hydrogen probes is to detect the amount of hydrogen permeating through the steel by mechanical or electrochemical measurement and to use this as a qualitative indication of corrosion rate.

Instrumentation

There exists a variety of instrument options associated with the various corrosion monitoring techniques. Three classifications are:

- Portable Meters and Data Loggers
- Field-Mounted Data Loggers
- Field-Mounted Transmitters

In some applications such as those experienced in oil/gas production and refining, instrumentation is required to be certified for use in "hazardous areas". For portable instruments this is most often achieved by having the equipment certified as "intrinsically safe" by a recognized authority such as BASEEFA (U.K.), U.L. (U.S.A.), ITS (U.S.A.), or CENELEC (Europe). For hardwired continuous monitoring electronics, isolation barriers can be used to ensure that, in the event of a fault condition, insufficient energy is transmitted to the hazardous field area for an explosive spark to be produced.

Probe Fitting Styles

There are two fundamental fitting styles for corrosion probes: fixed and removable under pressure.

Fixed styles of probes/sensors have typically a threaded or flanged attachment to the process plant. For fixed styles of sensors, removal can only be accomplished during system shut down or by isolation and depressurization of the sensor location.

From time to time, corrosion coupons and probes require removal and replacement. It is sometimes more convenient to be able to remove and install sensors while the process system is operational. To facilitate this, there are two distinct systems which permit removal/installation under pressure.

In refinery and process plant environments where pressures are normally less than 1500 psi, a Retractable System is used. This consists of a packing gland (stuffing box) and valve arrangement. For environments such as those experienced in oil/gas production where pressures of several thousand psi are experienced, a special High Pressure Access System is used. This permits the safe and easy installation/removal of corrosion monitoring devices at working pressures up to 3600 psi.

Applications of Corrosion Monitoring Techniques

Corrosion monitoring is typically used in the following situations:

- Where risks are high - high pressure, high temperature, flammable, explosive, toxic processes.
- Where process upsets can cause high corrosivity.
- Where changes in operating conditions can cause significant changes in corrosion rate.

- Where corrosion inhibitors are in use.
- In batch processes, where corrosive constituents are concentrated due to repeated cycling.
- Where process feedstock is changed.
- Where plant output or operating parameters are changed from design specifications.
- In the evaluation of corrosion behavior of various alloys.
- Where induced potential shifts are used to protect systems and/or structures.
- Where product contamination due to corrosion is a vital concern.

Corrosion monitoring may be used in virtually any industry where corrosion prevention is a primary requirement. Some examples of industries and specific areas of interest include, but are not limited to:

Oil/Gas Production
- Flowlines
- Gathering Systems
- Transport Pipelines
- Water Injection Facilities
- Vessels
- Processing
- Water Systems
- Chemical Injection Systems
- Drilling Mud Systems
- Water Wash Systems
- Desalters

Utilities
- Cooling Systems
- Effluent Systems
- Make-Up Water Systems
- Boiler Water Systems

Refining
- Crude Overheads
- Visbreakers
- Vacuum Towers
- Sour Water Strippers
- Amine Systems
- Cooling Systems

Pulp and Paper
- Digesters
- White Liquor
- Boiler Systems

Petrochemicals/Chemicals/Processing
- Process Systems
- Cooling Systems

In any corrosion monitoring system, it is common to find two or more of the techniques combined to provide a wide base for data gathering. The exact techniques which can be used depend on the actual process fluid, alloy system, and operating parameters.

Corrosion monitoring offers an answer to the question of whether more corrosion is occurring today as compared to yesterday. Using this information it is possible to qualify the cause of corrosion and quantify its effect. Corrosion monitoring remains a valuable weapon in the fight against corrosion, thereby providing substantial economic benefit to the user.

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Electrical Resistance Monitoring

(ER) Introduction

The electrical resistance (ER) technique is an "on-line" method of monitoring the rate of corrosion and the extent of total metal loss for any metallic equipment or structure. The ER technique measures the effects of both the electrochemical and the mechanical components of corrosion such as erosion or cavitation. It is the only on-line, instrumented technique applicable to virtually all types of corrosive environments.

Although universally applicable, the ER method is uniquely suited to corrosive environments having either poor or non-continuous electrolytes such as vapors, gases, soils, "wet" hydro-carbons, and nonaqueous liquids. Examples of situations where the ER approach is useful are:

- Oil/gas production and transmission systems
- Refinery/petrochemical process streams
- External surfaces of buried pipelines
- Feedwater systems
- Flue gas stacks
- Architectural structures

An ER monitoring system consists of an instrument connected to a probe. The instrument may be permanently installed to provide continuous information, or may be portable to gather periodic data from a number of locations. The probe is equipped with a sensing element having a composition similar to that of the process equipment of interest.

Principles of Operation

The electrical resistance of a metal or alloy element is given by:

$$R = r \cdot \frac{L}{A}$$

where:

L = Element length
A = Cross sectional area
r = Specific resistance

Reduction (metal loss) in the element's cross section due to corrosion will be accompanied by a proportionate increase in the element's electrical resistance.

Practical measurement is achieved using ER probes equipped with an element that is freely "exposed" to the corrosive fluid, and a "reference" element sealed within the probe body. Measurement of the resistance ratio of the exposed to reference element is made as shown in Figure 1.

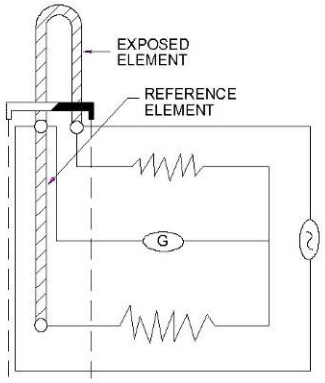


Figure 1. Probe / Instrument

Since temperature changes effect the resistance of both the exposed and reference element equally, measuring the resistance ratio minimizes the influence of changes in the ambient temperature. Therefore, any net change in the resistance ratio is solely attributable to metal loss from the exposed element once temperature equilibrium is established.

All standard Metal Samples Corrosion Monitoring Systems ER probes incorporate a third element called the "check" element. Because the check element is also sealed within the probe body, the ratio of its resistance to that of the reference element should remain unchanged. Any significant change in this ratio indicates a loss of probe integrity.

Measurement of the ER probe may either be taken periodically using a portable instrument, or on a continuous basis using a permanently installed unit. In either case, Metal Samples Corrosion Monitoring Systems ER instruments will produce a linearized signal which is proportional to the metal loss of the exposed element. The rate of change in the instrument output is a measure of the corrosion rate. Continuously monitored data is usually transmitted to a computer/data-logger and treated to give direct corrosion rate information. Manual graphing techniques are usually used to derive corrosion rate from periodically obtained data as illustrated in Figure 2.

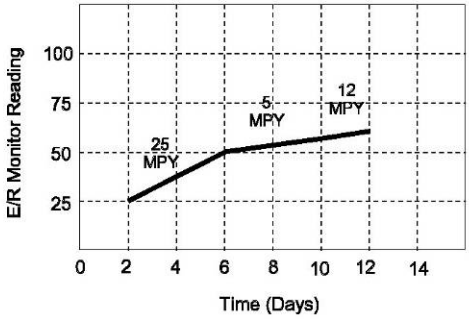


Figure 2. Graph plotting measurement versus time to derive corrosion rate.

ER Sensing Elements

Sensing elements are available in a variety of geometric configurations, thicknesses, and alloy materials. Available element types are shown in Figure 3.

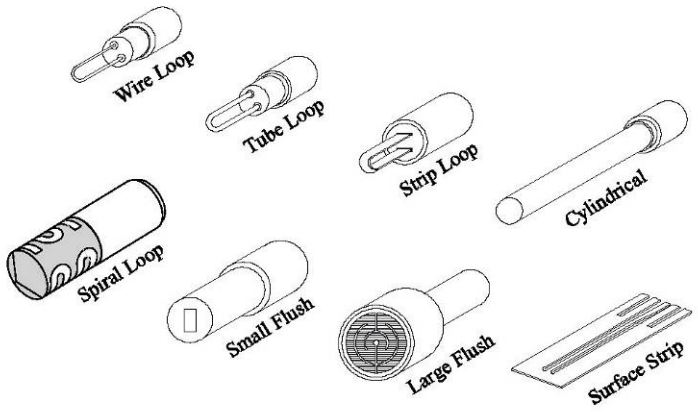


Figure 3. E/R Sensing Elements

Wire loop elements are the most common element available. This type of element has high sensitivity and low susceptibility to system noise, making it a good choice for most monitoring installations. Wire loops are generally glass-sealed into an endcap which is then welded to the probe body. The glass seal, which is chemically inert in most environments and has a good pressure and temperature rating, makes a good choice for most applications. Alloys commonly glass sealed are Carbon Steel, AISI 304 and 316 stainless steels. Where glass may be susceptible to corrosion problems, Teflon®-sealed elements are also available. Probes with wire loop elements are normally equipped with a flow deflector (or velocity shield) to protect the element from floating debris in the piping system.

Tube loop elements are recommended where high sensitivity is required to rapidly detect low corrosion rates. Tube loop elements are manufactured from a small bore, hollow tube formed into the above loop configuration. Carbon Steel is the alloy most commonly used. Tube loops sealed into the probe by a Teflon® pressure seal are also available. Probes using the tubular loop element can be equipped with a flow deflector to minimize possible distortion in fast flowing systems.

Strip loop elements are similar to the wire and tube loop configurations. The strip loop is a flat element formed in a loop geometry. The strip loop may be glass or epoxy sealed into the endcap depending on the required application. The strip loop is a very sensitive element. Strip loops are very fragile and should only be considered for very low flow applications.

Cylindrical elements are manufactured by welding a reference tube inside of a tube element. This element has an all welded construction which is then welded to the probe body. Because of this element's all welded construction, exotic alloy elements can be produced relatively easily. This probe is ideally suited to harsh environments including high velocity and high temperature systems, or anywhere a glass-sealed element is not an option.

Spiral loop elements consist of a thin strip of metal formed on an inert base. The element is particularly rugged and ideal for high-flow regimens. Its comparatively high resistance produces a high signal-to-noise ratio, which makes the element very sensitive.

Flush mount elements are designed to be mounted flush with the vessel wall. This element is very effective at simulating the true corrosion condition along the interior surfaces of the vessel wall. Being flush, this element is not prone to damage in high velocity systems and can be used in pipeline systems that are subject to pigging operations.

Surface strip elements are thin rectangular elements with a comparatively large surface area to allow more representative results in non-homogeneous corrosive environments. Strip elements are commonly used in underground probes to monitor the effectiveness of cathodic protection currents applied to the external surfaces of buried structures.

Corrosion Rate Calculation

When measuring the ER probe, the instrument produces a linearized signal (S) that is proportional to the exposed element's total metal loss (M). The true numerical value being a function of the element thickness and geometry. In calculating metal loss (M), these geometric and dimensional factors are incorporated into the "probe multiplier" (P), and the metal loss is given by:

$$M = \frac{S \times P}{1000}$$

Both S and P are dimensionless. Metal loss is conventionally expressed in mils (0.001 inches), as is element thickness.

Corrosion rate (C) is derived by:

$$C = \frac{P \times 365 \, (S_2 - S_1)}{\Delta T \times 1000}$$

ΔT being the lapse time in days between instrument readings S_1 and S_2.

Table 1 lists element types, thicknesses, probe life, and identification numbers. For temperature and pressure ratings see respective probe data sheets. When selecting an element type for a given application, the key parameters (apart from the fundamental constraints of temperature and pressure) in obtaining optimum results are *response time* and required *probe life*. Element thickness, geometry, and anticipated corrosion rate determine both response time and probe life. Response time, defined as the minimum time in which a measurable change takes place, governs the speed with which useful results can be obtained. Probe life, or the time required for the effective thickness of the exposed element to be consumed, governs the probe replacement schedule.

Element Type	Thickness	Probe Life	Element ID
Wire loop	40 mil 80 mil	10 mil 20 mil	WR40 WR80
Tube loop	4 mil 8 mil	2 mil 4 mil	TU04 TU08
Strip loop	5 mil 10 mil	1.25 mil 2.5 mil	SL05 SL10
Cylindrical	10 mil 20 mil 50 mil	5 mil 10 mil 25 mil	CT10 CT20 CT50
Spiral loop	10 mil 20 mil	5 mil 10 mil	SP10 SP20
Flush (small)	4 mil 8 mil 20 mil	2 mil 4 mil 10 mil	FS04 FS08 FS20
Flush (large)	5 mil 10 mil 20 mil 40 mil	2.5 mil 5 mil 10 mil 20 mil	FL05 FL10 FL20 FL40
Surface Strip	10 mil 20 mil 40 mil	5 mil 10 mil 20 mil	SS10 SS20 SS40

Table 1. Probe Life and Element ID

Since probe life and response time are directly proportional, element selection is a compromise between data frequency and probe replacement frequency. The graphical relationship between corrosion rate, probe life, and response time for all elements normally available from Metal Samples Corrosion Monitoring Systems is shown in Figure 4.

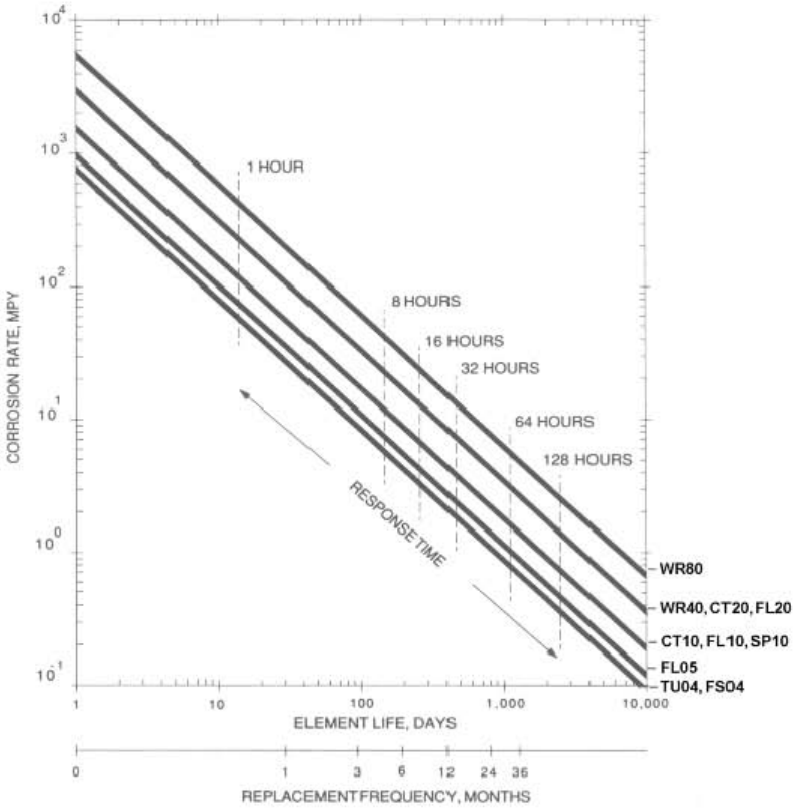


Figure 4. Element Selection Guide

Probe Features

Metal Samples Corrosion Monitoring Systems ER probes are available in a variety of configurations and are discussed in detail in later pages of this catalog. The brief summary provided here, gives only a broad overview of probe construction.

The standard material of construction for all Metal Samples Corrosion Monitoring Systems probe bodies is AISI 316L stainless steel which conforms with NACE specification MR-0175 for sour service conditions. Other materials may be available for extremely aggressive environments. Contact our sales department to discuss alternative options.

The primary pressure sealing mechanism for Metal Samples Corrosion Monitoring Systems E/R probes is the element seal, which varies with the precise element specification. However, all Metal Samples Corrosion Monitoring Systems process probes incorporate, at the instrument end, a glass-sealed, pressure-rated, electrical connector. The connector provides a backup seal should leakage develop in the element seal.

The simplest of all probe body configurations is the **fixed** version, shown in Figure 5. Typically equipped with an NPT pipe plug or flange connection, the fixed probe is screwed or bolted into place. Probe installation or removal can only be performed during shut-down, unless the probe is installed in a side-stream which may be isolated and depressurized. The frequency of shut-down should be a factor in the selection of probe life criteria.

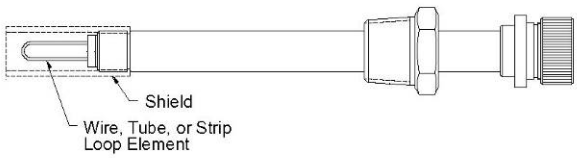


Figure 5. Fixed Probe

Retractable probes are supplied with a 1-inch FNPT packing gland to allow probe insertion and removal through a customer-supplied ball valve, in systems with pressures not exceeding 1500 psi. A safety frame of rods and plates may be attached to the probe to prevent "backing out" in systems with high vibration. Metal Samples Corrosion Monitoring Systems requires the Easy Tool for probe insertion or retraction in systems with pressure over 150 pounds.

Retractable probes find wide applications in refinery and petrochemical industries. A typical probe is shown in Figure 6.

Retrievable probes are employed in process systems operating at pressures up to 3600 psi. These probes must be used in conjunction with specially designed fittings, retrieval tools and service valves, all of which are described in the High Pressure Access Systems section. The retrievable design is the industry standard for oil production systems. A typical installation is shown in Figure 7.

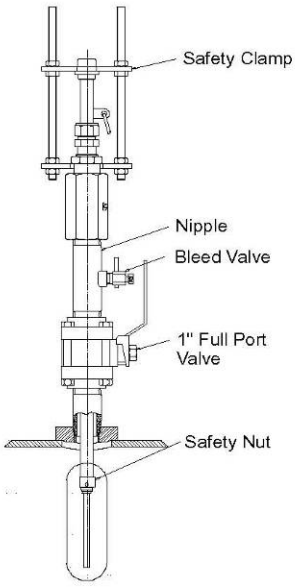


Figure 6. Retractable Probe

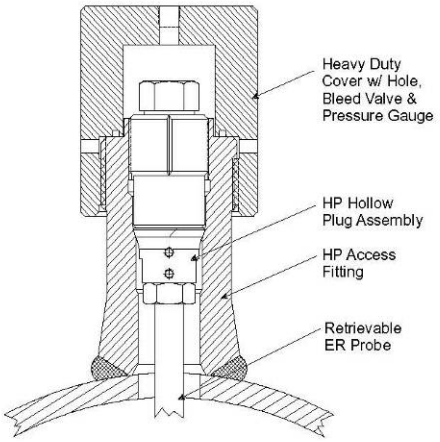
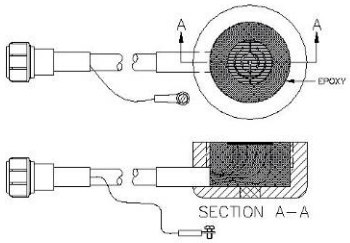


Figure 7. Retrievable Probe

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Model ER0500

Electrical Resistance Probe
Surface Strip Element and Cylindrical Element Types



Surface Strip Element



Cylindrical Element

Model ER0500 probes are designed for heavy duty service conditions such as underground and structural monitoring of pipelines, vessels, above and below ground storage tanks and structures - whether cathodically protected or not. The surface strip element assembly is suited to the "construction site" environment. The cylindrical element is economical and durable. Its slim profile is convenient for locations with restricted access such as concrete bridge structures and other infrastructure applications. Both probes provide good sealing of the reference element and the check element provides confidence in the continued performance of the corrosion sensor. Either probe may or may not be connected to a cathodically protected structure. Connection of a ground cable allows the probe to measure the effectiveness of the Cathodic Protection (C.P.) System under all the operating conditions. If unconnected to the structure, the probe monitors the direct corrosivity of the soil or environment. The probes may be ordered with or without a grounding lead for a C.P. System. The lead may be installed at the probe or connector end, whichever is most convenient. In most cases, a lead at the monitoring connector end is preferred, with a separate lead running to the vessel or C.P. System. This enables connection to the C.P. System to be made as required - even after probe installation.

Specifications:

	Surface Strip	Cylindrical
Probe Body	Epoxy Block	All Welded Element
Cable Connection	Heavy Duty Length	Heavy Duty Length with Bonded Heat Shrink Sleeving onto Element

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ER0500 Ordering Information

Model					
AP	Electrical Resistance Probe				
	Type				
	31	Under ground surface strip without ground strap			
	40	Under ground cylindrical with ground strap			
	61	Under ground surface strip with ground strap			
	70	Under ground cylindrical without ground strap			
		Element Thickness			
		10	10 mil thickness (5 mil useful probe life) - cylindrical or surface strip		
		20	20 mil thickness (10 mil useful probe life) - cylindrical or surface strip		
		40	40 mil thickness (20 mil useful probe life) - surface strip only		
		50	50 mil thickness (25 mil useful probe life) - cylindrical only		
			Element Alloy		
			XXX	Use Code in Alloy Chart	
				Cable Length	
				10	10 ft cable
				20	20 ft cable
AP	**31**	**40**	**375**	**20**	**Example of Probe Ordering #**

For alloys, sizes, or other special requirements not listed, contact our sales department.

Alloy Chart					
Code	**Description**	**UNS #**	**Code**	**Description**	**UNS #**
375	C1010	G10100	159	316L SS	S31603
538	5Cr 1/2Mo	K42544	A12	C276	N10276
541	9Cr 1Mo	K90941	602	Alloy 625	N06625
186	410 SS	S41000	419	CDA110	C11000
141	304 SS	S30400	434	CDA443	C44300

Note: Not all alloys are available with all element types and seals.

Corrosion Coupons and Weight Loss Analysis

Introduction



The simplest, and longest-established, method of estimating corrosion losses in plant and equipment is weight loss analysis. A weighed sample (coupon) of the metal or alloy under consideration is introduced into the process, and later removed after a reasonable time interval. The coupon is then cleaned of all corrosion product and is reweighed. The weight loss is converted to a corrosion rate (CR) or a metal loss (ML), as follows:

$$\text{Corrosion Rate (CR)} = \frac{\text{Weight loss (g)} * K}{\text{Alloy Density (g/cm}^3\text{)} * \text{Exposed Area (A)} * \text{Exposure Time (hr)}}$$

The constant can be varied to calculate the corrosion rate in various units:

Desired Corrosion Rate Unit (CR)	Area Unit (A)	K-Factor
mils/year (mpy)	in^2	5.34×10^5
mils/year (mpy)	cm^2	3.45×10^6
millimeters/year (mmy)	cm^2	8.75×10^4

$$\text{Metal Loss (ML)} = \frac{\text{Weight loss (g)} * K}{\text{Alloy Density (g/cm}^3\text{)} * \text{Exposed Area (A)}}$$

Desired Metal Loss Unit (ML)	Area Unit (A)	K-Factor
mils	in^2	61.02
mils	cm^2	393.7
millimeters	cm^2	10.0

The technique requires no complex equipment or procedures, merely an appropriately shaped coupon, a carrier for the coupon (coupon holder), and a reliable means of removing corrosion product without disruption of the metal substrate. Weight loss measurement is still the most widely used means of determining corrosion loss, despite being the oldest method currently in use.

Weight loss determination has a number of attractive features that account for its sustained popularity:

- Simple - No sophisticated instrumentation is required to obtain a result.
- Direct - A direct measurement is obtained, with no theoretical assumptions or approximations.
- Versatile - It is applicable to all corrosive environments, and gives information on all forms of corrosion.

The method is commonly used as a calibration standard for other means of corrosion monitoring, such as Linear Polarization and Electrical Resistance. In instances where slow response and averaged data are acceptable, weight loss monitoring is the preferred technique.

Coupon Preparation and Cleaning

The choice of technique for initial preparation of the coupon surface, and for cleaning the coupon after use, is critical in obtaining useful data. Both the relevance and reproducibility of weight loss data are highly sensitive to the inherent suitability of these techniques, and to the care with which they are executed.

Surface finishing methods vary across a broad range for specific applications. Blasting with glass bead, sand, or other aggregate can provide an acceptable finish for some applications. Sanding with abrasive belts, or surface or double disc grinding with abrasive stones also provides an excellent surface for evaluation.



Coupon after being exposed to corrosive environment.

Cleaning of specimens before weighing and exposure is critical to remove any contaminants that could affect test results.

Reference should be made to NACE Recommended Practice RP-0775 and ASTM G-1 & G-4 for further detail on surface finishing and cleaning of weight-loss coupons.

Coupon Position and Orientation

Irrespective of the degree of care exercised in the surface preparation of coupons, many uncontrollable factors (e.g. microstructural defects) can reduce the accuracy of weight loss determinations. Therefore, using duplicate (Figure 1) or multi-replicate (Figure 2) coupon samples is considered good practice.

Coupon orientation must be consistent in order to make different data sets comparable. Generally, an orientation parallel to the process flow is preferable since this more nearly reflects the true condition experienced by the vessel wall (Figure 1). Metal Samples Corrosion Monitoring Systems MH™ coupon holders have an automatic flow alignment feature. All other holders are marked on the top side with flow direction for manual alignment.

Positioning is another critical factor in obtaining relevant information. For example, a multi-phase product may produce layered flow, giving rise to corrosion rates that vary with depth in the process stream. Such situations can be monitored with a ladder-strip coupon holder (Figure 2).

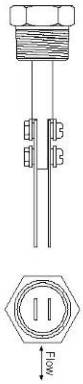


Figure 1. Preferred Flow Direction



Figure 2. Ladder Strip Coupon Holder

Possibly the most common issue in coupon positioning arises from the fact that a true representation of the corrosion experienced by the pipe/vessel can only be established when the weight loss coupon is in the plane of the vessel/pipe wall. Only in this position can the coupon experience the same flow regime as the pipe surface being monitored. In response to this situation, the use of flush-disc coupons has become widespread (Figure 3).

The general issue of coupon orientation and positioning in relation to flow regime, plant geometry, and process fluid is complex and tends to be specific to each application. However, the most common coupon configurations have been discussed above.

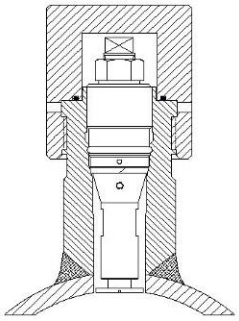


Figure 3. Flush Disc Coupon Holder in High Pressure Access Fitting

Coupon Holders

Specific design of coupon holders incorporates two basic factors:

- Number, style, and configuration of coupons
- System entry method

Fixed (Pipe Plug) Coupon Holders

The simplest system entry design for coupon holders is the fixed or pipe plug coupon holder (Figure 4). This type of coupon holder is normally offered on a ¾", 1", or 2" NPT pipe-plug. The size of the plug to be used is the limiting factor as to the coupon configuration that can be used. These coupon holders are usually constructed in AISI 316L stainless steel, have a pressure rating of 3000 psi, and a temperature rating of 450°F/232°C. This design of coupon holder is recommended for use in a by-pass loop which can be isolated, or in systems having frequent and regular shut-down, since system depressurization is required during insertion and removal.

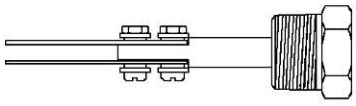


Figure 4. Fixed (Pipe Plug) Coupon Holder

Retractable Coupon Holders

A design that is commonly used in the refining and petrochemical industry is the retractable type coupon holder as shown in Figure 5. This coupon holder design employs a packing gland that allows insertion and removal, through a ball-valve, without system depressurization. A safety cable and safety nut are also provided to prevent blowout. Retractable coupon holders can be used up to 1500 psi and 500°F (260°C), and are constructed of AISI 316L stainless steel. Normally, a 1" FNPT packing gland is used in conjunction with either a 1", or a 1½" full port ball valve, depending on the type of coupon configuration chosen. (See the RT4000 sheet for more information.)

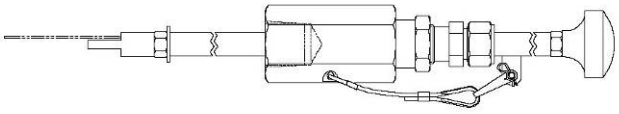


Figure 5. Retractable Coupon Holder

Retrievable Coupon Holders

The oil and gas production industry generally employs retrievable coupon holders that operate with high pressure access systems. This will allow insertion/removal under pressures up to 3600 psi. Metal Samples Corrosion Monitoring Systems supplies both generic (HP™) and proprietary (MH™) coupon holders. (See Coupon Holders for High Pressure Access Systems.)

The retrievable coupon holder is installed on to the solid plug. The assembly can then be inserted or removed from the system using a special service valve and retrieval tool.

Retrievable coupon holders are generally constructed in AISI 316L stainless steel to meet the requirements of NACE standard MR-0175 for sour service use. These are available for all standard coupon configurations.

Retrievable, retractable, and pipe plug style coupon holders cover the needs of most industries and applications. However, the requirement for special coupon holder designs is significant, and Metal Samples Corrosion Monitoring Systems has the facility to design and build coupon holders to any customer-supplied specification.

Metal Samples Corrosion Monitoring Systems
A Division of Alabama Specialty Products, Inc.
152 Metal Samples Rd., Munford, AL 36268 Phone: (256) 358-4202 Fax: (256) 358-4515
E-mail: msc@alspi.com Internet: www.metalsamples.com
Houston Office: 8811 Kensington Court, LaPorte, TX 77571 Phone: (281) 471-2777 Fax: (281) 471-3405

Appendix E: Corrosion Control, Inc., Report on Coupon and Electrical Resistance Sensor Tests

CORROSION CONTROL INCORPORATED

Professional Personalized Service

July 27, 2007

Mandaree Enterprise
812 Park Drive
Warner Robins, Georgia

Attention: Mr. Larry O. Cranford
Senior Contracts Manager

Reference: Tori Station Corrosion Rate
Instrument comparison
Contract W9132T-06-D-0001
Task Orders No. 2 and 5
Eight (8) Month Inspection
REVISED FEBRUARY 2008

Dear Mr. Cranford:

As you are aware Corrosion control Incorporated completed the installation of the corrosion monitoring devices at Tori Station in Okinawa, Japan in November of 2006. In accordance with the CERL scope of work, this project involves the comparison of corrosion rate monitoring instruments. Under task order No. 2, twelve (12) weight loss coupons were installed on two (2) exposure racks. Under task order No. 5, six (6) electronic resistance corrosion rate probes were installed in close proximity to the exposure racks. Under a separate contract, Analatom installed a miniature corrosion monitoring probe, with remote monitoring capabilities. The miniature probe was to be installed near the other monitoring devices. The corrosion rates are to be monitored, using the three (3) methods, over an eight (8) month period. The resulting corrosion loss rates are then to be compared, using the coupons as a standard.

Installation:

Our senior engineer and technician arrived at Tori Station on November 1, 2006. A meeting was held with Mr. Daniel Zrna of Public Works. During this initial meeting, it was discovered that the photographs provided for the building to mount the instrumentation, were

494 Fairplay Street
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Phone 706-557-9624
Fax 706-557-7923

actually two (2) separate buildings. Building No. 270 is located about 2 kilometers from the ocean, is 25 feet tall, and is scheduled for demolition in 2007. The second building shown in our submittal is actually No. 125. This building is 1.5 kilometers from the ocean, and has good work access. The tenant of building No. 125 was also eager to have the study conducted, due to reoccurring corrosion problems. Mr. Zrna agreed that building No. 125 would be a good choice.

Once the building had been selected, our engineer and technician installed the coupon racks and resistance probes. The coupons were mounted to an aluminum frame using stainless steel bolts and nylon spacer washers. Stainless steel bolts were used in place of nylon bolts to withstand high wind loads. The coupons are electrically isolated. The resistance probe cables were secured to the roof, and run down the outside wall in conduit. The ends of the probe cables were gathered in a NEMA 4X test box. Signs were posted to ensure no one removes the instruments. The local DPW added their phone number to the signs. See the enclosed photographs and drawings.

Our engineer recorded initial readings on the resistance probes. Within four (4) days, the coupons and probes had flash rusted. This area is fairly corrosive, with elevated levels of air borne salts and significant rain fall. Our technician would then schedule to monitor the probes and retrieve coupons during the first weeks of January, March, May and July of 2007.

2 Month Inspection:

Our technician visited the test site on January 8, 2007. Upon arrival, the exposure coupons, corrosion probes and test box were found undisturbed. Photographs of the coupons and probes are provided in attachment No. 1. All of the coupons and probes are covered with corrosion product. Once photographs had been obtained, three (3) coupons were removed from each exposure rack. The coupons were removed with care, and placed in numbered brown paper envelopes, furnished by the coupon manufacturer. The envelopes were sealed, and then placed in a plastic envelope, which was in turn placed in an overnight delivery envelope. The envelope was express shipped to Metal Samples for analysis, along with a chain of custody letter.

Upon receipt at Metal Samples, the coupons were cleaned and weighed. The net metal and rate of corrosion was then calculated by the laboratory. This data is provided in attachment No. 5. Coupons No. 1, 2 and 3 are from exposure rack No. 1, and coupons No. 13, 14 and 15 are from exposure rack No. 2. See drawing A-1979-1 of attachment No. 13, for the exposure rack locations. In review, the metal loss experienced by the coupons ranged from 1.5397 to 1.7517 mils per year. The metal loss at exposure rack No. 1 is 1.6834 mpy on average. The metal loss at exposure rack No. 2 is 1.5538 mpy on average. The average realized corrosion rate is 0.1293 mpy or 8.3 percent higher on rack No. 1 than rack No. 2. This difference is likely due to the predominant wind direction. The average realized corrosion rate for all six (6) coupons was 1.6186 mpy.

The laboratory returned the coupons to our office after cleaning and analysis. All of the coupons exhibited etching of the surface, with some very shallow pitting. No selective pitting corrosion was apparent.

While on site our technician also recorded the electronic resistances on the corrosion probes. This data is provided within attachment No. 9. The location of the probes, in relation to the exposure racks, is shown on drawing A-1979-1 of attachment No. 13. In review, the corrosion probes registered a rate of corrosion ranging from 1.02 to 2.17 mils per year. The average rate of corrosion realized by the six (6) probes was 1.43 mpy.

Based on the two (2) month exposure results, the electronic resistance corrosion probes were registering, on average, 0.1886 mpy less corrosion than the exposure coupons. There was a significant difference (@13%) in registered corrosion rates between the coupons and probes, at two (2) months.

4 Month Inspection:

Our technician re-visited the test site on March 6, 2007. Upon arrival, the exposure coupons, corrosion probes and test box were found undisturbed. Photographs of the coupons and probes are provided in attachment No. 2. All of the remaining coupons and probes are covered with corrosion product. Once photographs had been obtained, three (3) coupons were removed from each exposure rack. The coupons were removed with care, and placed in numbered brown paper envelopes, furnished by the coupon manufacturer. The envelopes were sealed, and then placed in a plastic envelope, which was in turn placed in an overnight delivery envelope. The envelope was express shipped to Metal Samples for analysis, along with a chain of custody letter.

Upon receipt at Metal Samples, the coupons were cleaned and weighed. The net metal and rate of corrosion was then calculated by the laboratory. This data is provided in attachment No. 6. Coupons No. 4, 5 and 6 are from exposure rack No. 1, and coupons No. 16, 17 and 18 are from exposure rack No. 2. See drawing A-1979-1 of attachment No. 13, for the exposure rack locations. In review, the metal loss experienced by the coupons ranged from 1.3393 to 1.4338 mils per year. The metal loss at exposure rack No. 1 is 1.3789 mpy on average. The metal loss at exposure rack No. 2 is 1.4015 mpy on average. The average realized corrosion rate is 0.0226 mpy or 1.6 percent higher on rack No. 2 than rack No. 1. This is a reversal from the two (2) month results, the corrosion rates are now more uniform and lower. The average realized corrosion rate for all six (6) coupons at four months was 1.3902 mpy.

The laboratory returned the coupons to our office after cleaning and analysis. All of the coupons exhibited etching of the surface, with scattered shallow pitting. The pitting is most significant on the bottom of each coupon, toward the middle.

While on site, our technician also recorded the electronic resistances on the corrosion probes. This data is provided within attachment No. 10. The location of the probes, in relation to the exposure racks, is shown on drawing A-1979-1 of attachment No. 13. In review, the corrosion probes registered a rate of corrosion ranging from 0.77 to 1.55 mils per year. The average rate of corrosion realized by the six (6) probes was 1.12 mpy.

Based on the four (4) month exposure results, the electronic resistance corrosion probes were registering, on average, 0.27 mpy less corrosion than the exposure coupons. The corrosion rates were becoming more uniform, and were slightly reduced.

6 Month Inspection:

Our technician re-visited the test site on May 7, 2007. Upon arrival, the exposure coupons, corrosion probes and test box were found undisturbed. Photographs of the coupons and probes are provided in attachment No. 3. All of the remaining coupons and probes are covered with corrosion product. Once photographs had been obtained, three (3) coupons were removed from each exposure rack. The coupons were removed with care, and placed in numbered brown paper envelopes, furnished by the coupon manufacturer. The envelopes were sealed, and then placed in a plastic envelope, which was in turn placed in an overnight delivery envelope. The envelope was express shipped to Metal Samples for analysis, along with a chain of custody letter.

Upon receipt at Metal Samples, the coupons were cleaned and weighed. The net metal and rate of corrosion was then calculated by the laboratory. This data is provided in attachment No. 7. Coupons No. 7, 8 and 9 are from exposure rack No. 1, and coupons No. 19, 20 and 21 are from exposure rack No. 2. See drawing A-1979-1 of attachment No. 13, for the exposure rack locations. In review, the metal loss experienced by the coupons ranged from 1.2043 to 1.2677 mils per year. The metal loss at exposure rack No. 1 is 1.2297 mpy on average. The metal loss at exposure rack No. 2 is 1.2461 mpy on average. The average realized corrosion rate is 0.0164 mpy or 0.9 percent higher on rack No. 2 than rack No. 1. This is about the same as the four (4) month results and the corrosion rates are even more uniform and lower. The average realized corrosion rate for all six (6) coupons at six months was 1.2379 mpy.

The laboratory returned the coupons to our office after cleaning and analysis. All of the coupons exhibited etching of the surface, with scattered shallow pitting. The pitting is most significant on the bottom of each coupon, toward the middle. The bottom side would stay moister.

While on site, our technician also recorded the electronic resistances on the corrosion probes. This data is provided within attachment No. 11. The location of the probes, in relation to the exposure racks, is shown on drawing A-1979-1 of attachment No. 13. In review, the

corrosion probes registered a rate of corrosion ranging from 0.92 to 1.46 mils per year. The average rate of corrosion realized by the six (6) probes was 1.06 mpy.

Based on the six (6) month exposure results, the electronic resistance corrosion probes were registering, on average, 0.18 mpy less corrosion than the exposure coupons. All the corrosion rates were becoming more uniform, and the separation between the coupon and probe rates was reduced, between the four (4) and six (6) month inspections.

8 Month Inspection:

Our technician re-visited the test site on July 2, 2007. Upon arrival, the exposure coupons, corrosion probes and test box were found undisturbed. Photographs of the coupons and probes are provided in attachment No. 4. All of the remaining coupons and probes are covered with corrosion product. Once photographs had been obtained, three (3) coupons were removed from each exposure rack. The coupons were removed with care, and placed in numbered brown paper envelopes, furnished by the coupon manufacturer. The envelopes were sealed, and then placed in a plastic envelope, which was in turn placed in an overnight delivery envelope. The envelope was express shipped to Metal Samples for analysis, along with a chain of custody letter.

Upon receipt at Metal Samples, the coupons were cleaned and weighed. The net metal and rate of corrosion was then calculated by the laboratory. This data is provided in attachment No. 8. Coupons No. 10, 11 and 12 are from exposure rack No. 1, and coupons No. 22, 23 and 24 are from exposure rack No. 2. See drawing A-1979-1 of attachment No. 13, for the exposure rack locations. In review, the metal loss experienced by the coupons ranged from 1.1656 to 1.2812 mils per year. The metal loss at exposure rack No. 1 is 1.2400 mpy on average. The metal loss at exposure rack No. 2 is 1.2000 mpy on average. The average realized corrosion rate is 0.0164 mpy or 3 percent higher on rack No. 1 than rack No. 2. This is about the same as the four (4) month results and the corrosion rates are even more uniform and lower. The average realized corrosion rate for all eight (8) coupons at six months was 1.2200 mpy.

The laboratory returned the coupons to our office after cleaning and analysis. All of the coupons exhibited etching of the surface, with scattered shallow pitting. The pitting is most significant on the bottom of each coupon, toward the middle. The bottom side would stay moister.

While on site, our technician also recorded the electronic resistances on the corrosion probes. This data is provided within attachment No. 11. The location of the probes, in relation to the exposure racks, is shown on drawing A-1979-1 of attachment No. 13. In review, the corrosion probes registered a rate of corrosion ranging from 0.92 to 1.39 mils per year. The average rate of corrosion realized at eight months by the six (6) probes was 1.06 mpy.

Mandaree Enterprise
Mr. Larry O. Cranford
July 27, 2007
REVISED FEBRUARY 2008
Page 6

Based on the eight (8) month exposure results, the electronic resistance corrosion probes were registering, on average, 0.16 mpy less corrosion than the exposure coupons. All of the corrosion rates were increasingly more uniform, and the separation between the coupon and probe rates dropped slightly, between the six (6) and eight (8) month inspections. The variance between the probes and coupons is likely due to the way they are exposed. The probes are exposed on the top side only. The coupons are exposed horizontally, and had a shaded side that tended to hold moisture.

This is the last inspection.

Respectfully Submitted,
CORROSION CONTROL INCORPORATED



Craig K. Meier VP
Principal Corrosion Engineer
NACE Cathodic Protection Specialist #6552
DOT/OPS #00835471

#779

ATTACHMENT NO. 1

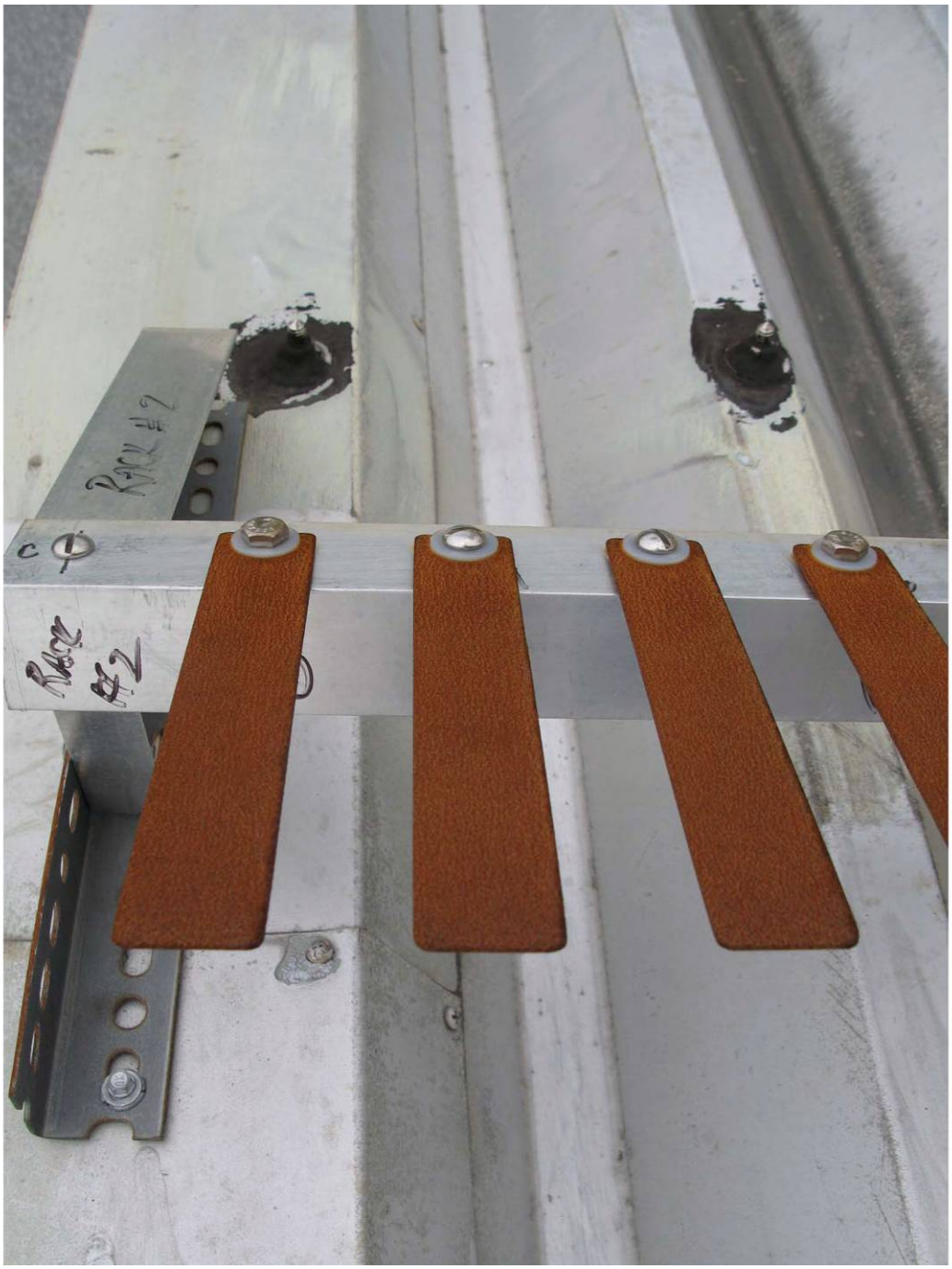
PHOTOGRAPHS

TWO MONTHS

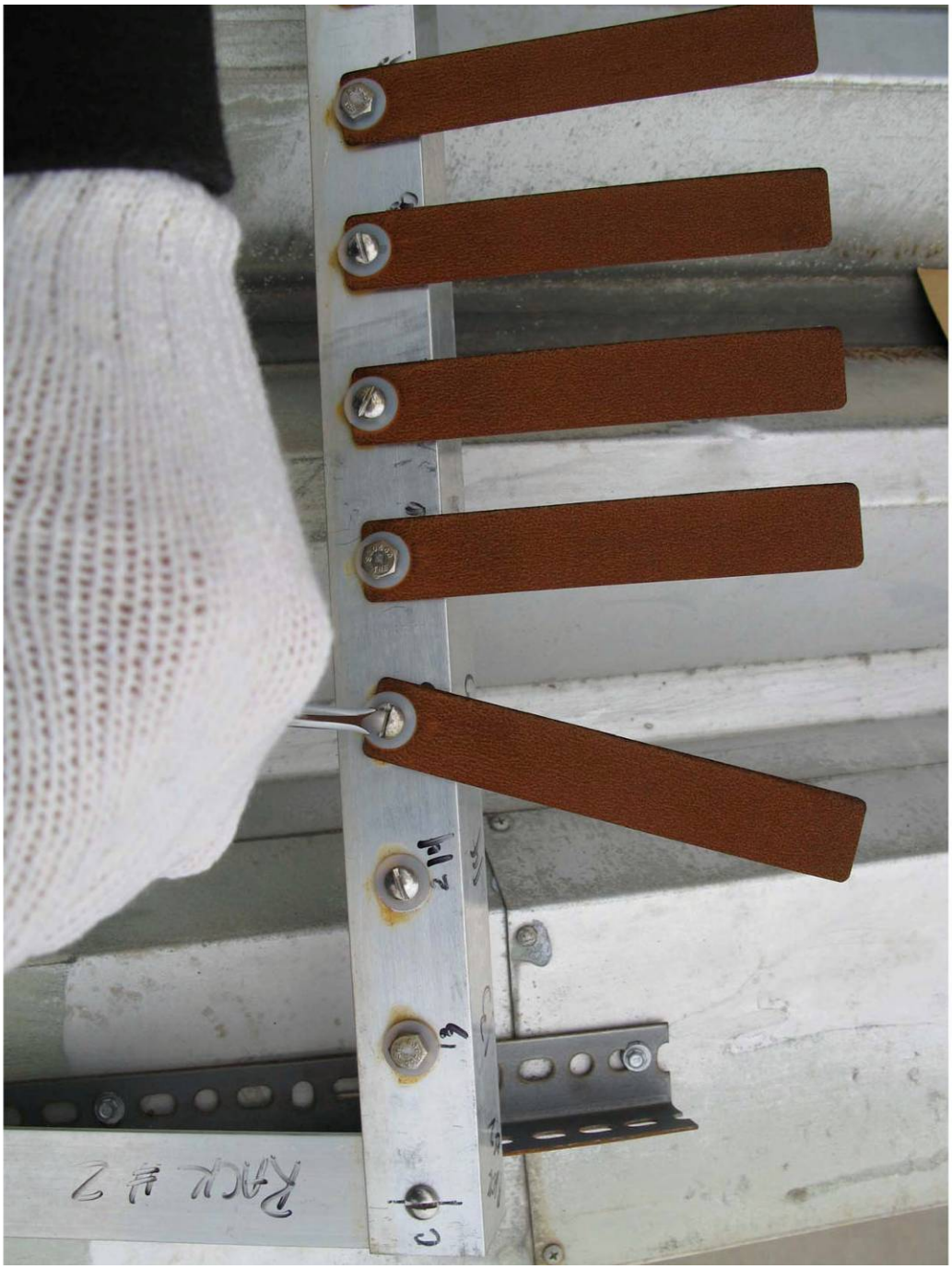







RACK #2

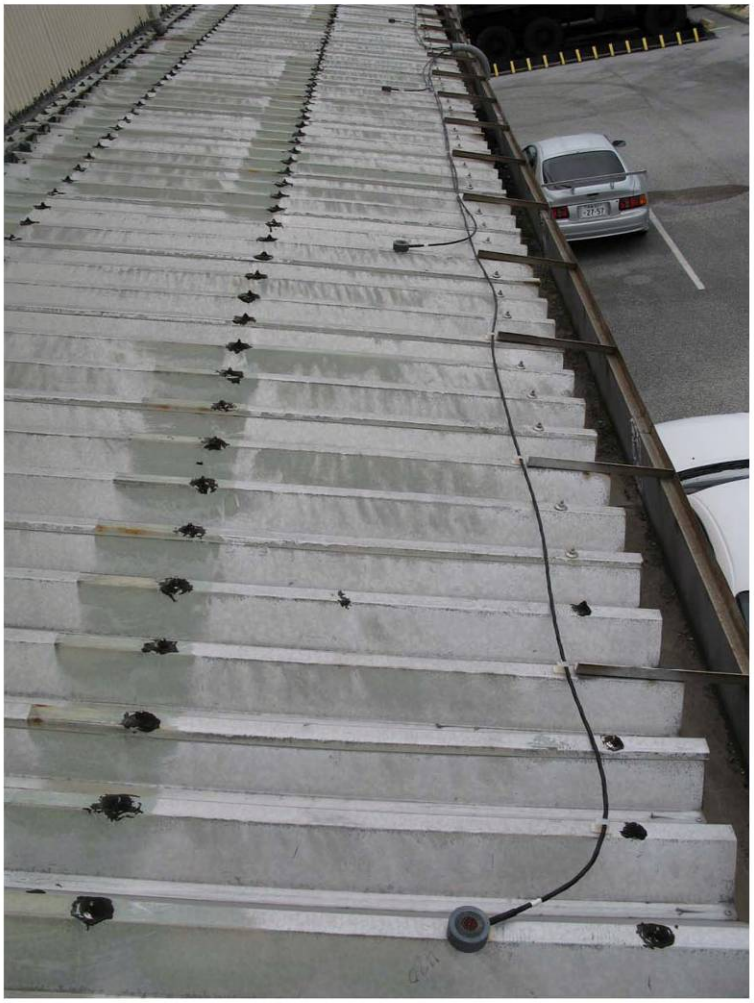




ATTACHMENT NO. 2

PHOTOGRAPHS

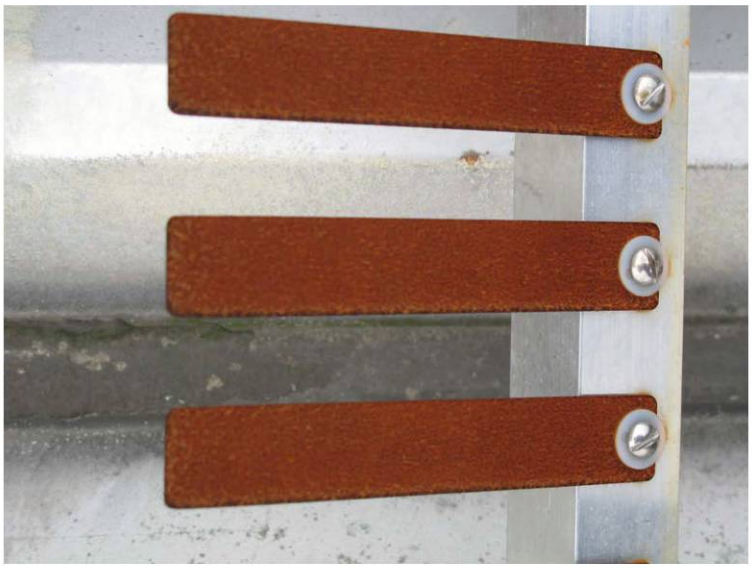
FOUR MONTHS



01. View of corrosion probes on roof.



02. Coupon rack No. 1 at 4 months.



03. Close up of coupons No. 4, 5 and 6, rack No. 1.



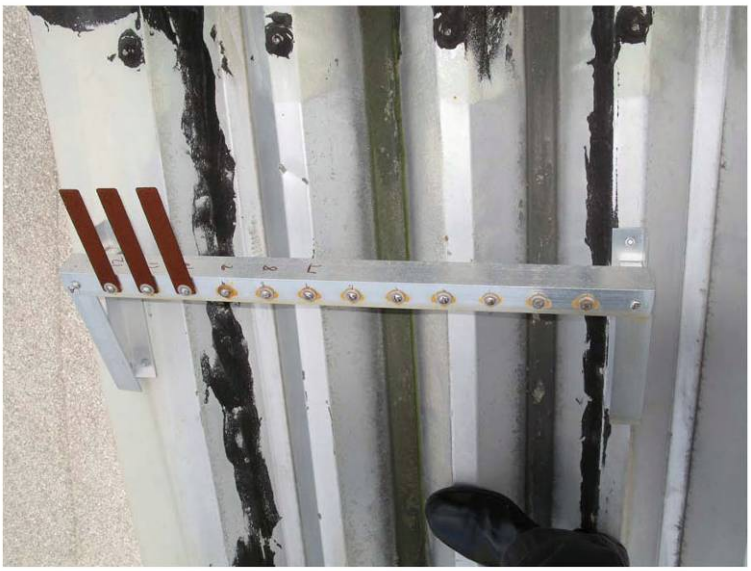
04. Close up of coupons No. 16, 17 and 18, rack No. 2.

ATTACHMENT NO. 3

SIX MONTH PHOTOGRAPHS



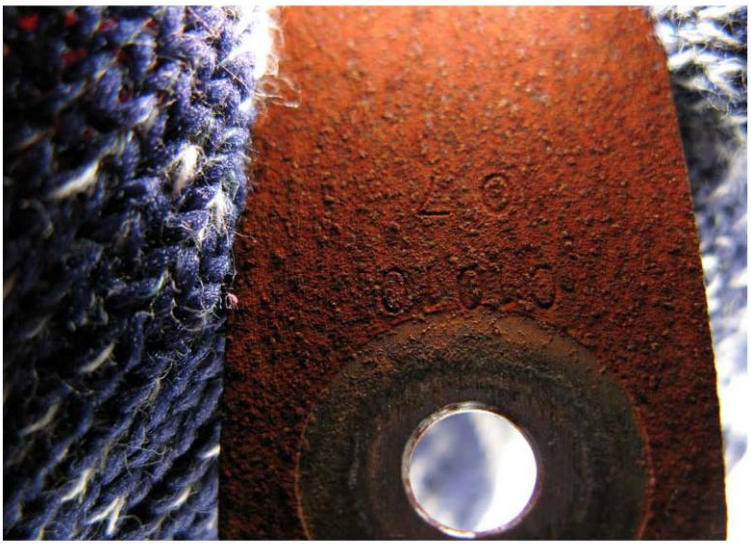
01. Corrosion coupons before 6 month removal.



02. Corrosion Coupons after 6 month removal.



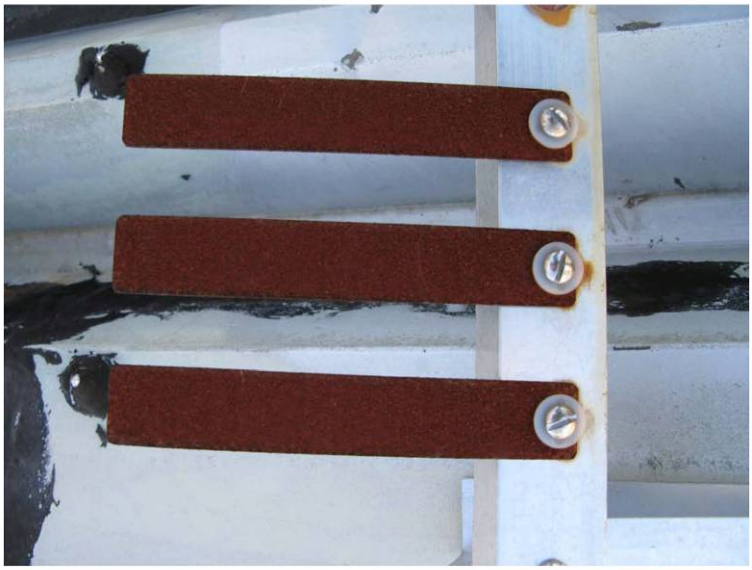
03. Close-up of mounted corrosion coupon before removal.



04. Close-up of typical corrosion coupon after removal.

ATTACHMENT NO. 4

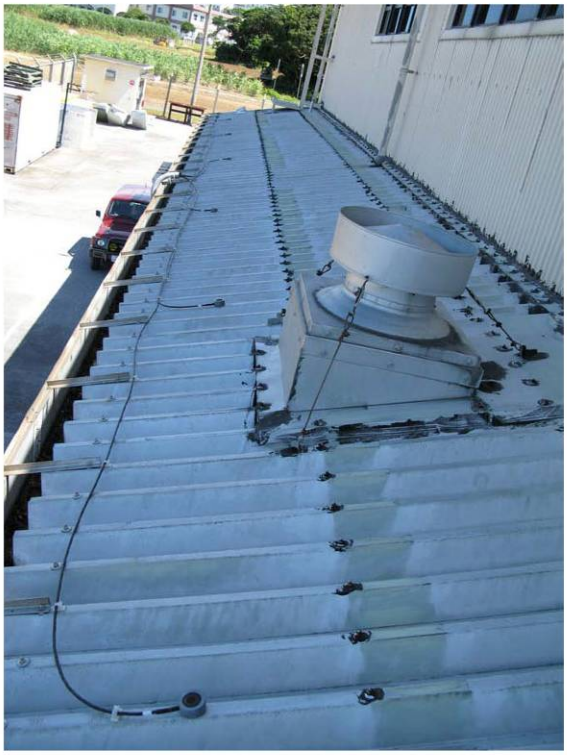
EIGHT MONTH PHOTOGRAPHS



01. View of rack #1 before removing coupons



02. View of rack #2 before removing coupons



03 View of corrosion resistance probes

#766

ATTACHMENT NO. 5

COUPON DATA

TWO MONTHS

Date: 1/31/2007 Page: 1

Metal Samples,Co., Inc.
Phone: (256) 358-4202
Corrosion Analysis Data Report

Customer : CORROSION CONTROL, INC Shop Order : 98938
Purchase Order: MAIL ORDER

Alloy	:	C1010	ID Number	:	01
Initial Weight	:	40.8674	Installed	:	11/1/2006
Final Weight	:	40.3337	Removed	:	1/8/2007
Weight Loss	:	0.5337	Hours Exposed	:	1632
Density (g/cm3)	:	7.8700	Surface Area (in2)	:	12.6806

Mils Per Year : 1.7517
Comments : AREAS OF ATTACK
Location : TORI STATION

Alloy	:	C1010	ID Number	:	02
Initial Weight	:	42.2031	Installed	:	11/1/2006
Final Weight	:	41.6995	Removed	:	1/8/2007
Weight Loss	:	0.5036	Hours Exposed	:	1632
Density (g/cm3)	:	7.8700	Surface Area (in2)	:	12.6806

Mils Per Year : 1.6529
Comments : AREAS OF ATTACK/SPOTTY ETCH
Location : TORI STATION

Alloy	:	C1010	ID Number	:	03
Initial Weight	:	42.4366	Installed	:	11/1/2006
Final Weight	:	41.9352	Removed	:	1/8/2007
Weight Loss	:	0.5014	Hours Exposed	:	1632
Density (g/cm3)	:	7.8700	Surface Area (in2)	:	12.6806

Mils Per Year : 1.6457
Comments : AREAS OF ATTACK/SPOTTY ETCH
Location : TORI STATION

Alloy	:	C1010	ID Number	:	13
Initial Weight	:	40.7976	Installed	:	11/1/2006
Final Weight	:	40.3200	Removed	:	1/8/2007
Weight Loss	:	0.4776	Hours Exposed	:	1632
Density (g/cm3)	:	7.8700	Surface Area (in2)	:	12.6806

Mils Per Year : 1.5676
Comments : AREAS OF ATTACK/SPOTTY ETCH
Location : TORI STATION

Date: 1/31/2007 Page: 2

Metal Samples,Co., Inc.
Phone: (256) 358-4202
Corrosion Analysis Data Report

Customer : CORROSION CONTROL, INC Shop Order : 98938
Purchase Order: MAIL ORDER

Alloy	:	C1010	ID Number	:	14
Initial Weight	:	42.0023	Installed	:	11/1/2006
Final Weight	:	41.5332	Removed	:	1/8/2007
Weight Loss	:	0.4691	Hours Exposed	:	1632
Density (g/cm3)	:	7.8700	Surface Area (in2)	:	12.6806

Mils Per Year : 1.5397
Comments : AREAS OF ATTACK/SPOTTY ETCH
Location : TORI STATION

Alloy	:	C1010	ID Number	:	15
Initial Weight	:	42.3949	Installed	:	11/1/2006
Final Weight	:	41.9214	Removed	:	1/8/2007
Weight Loss	:	0.4735	Hours Exposed	:	1632
Density (g/cm3)	:	7.8700	Surface Area (in2)	:	12.6806

Mils Per Year : 1.5541
Comments : AREAS OF ATTACK/SPOTTY ETCH
Location : TORI STATION

ATTACHMENT NO. 6

COUPON DATA

FOUR MONTHS

Date: 3/15/2007 Page: 1

Metal Samples,Co., Inc.
Phone: (256) 358-4202
Corrosion Analysis Data Report

Customer : CORROSION CONTROL, INC Shop Order : 99974
Purchase Order: MAIL ORDER

Alloy	:	C1010	ID Number	:	04
Initial Weight	:	42.6707	Installed	:	11/1/2006
Final Weight	:	41.8961	Removed	:	3/6/2007
Weight Loss	:	0.7746	Hours Exposed	:	3000
Density (g/cm3)	:	7.8700	Surface Area (in2)	:	12.7721

Mils Per Year	:	1.3732
Comments	:	AREAS OF ATTACK
Location	:	CORROSION CONTROL IN

Alloy	:	C1010	ID Number	:	05
Initial Weight	:	42.4944	Installed	:	11/1/2006
Final Weight	:	41.7023	Removed	:	3/6/2007
Weight Loss	:	0.7921	Hours Exposed	:	3000
Density (g/cm3)	:	7.8700	Surface Area (in2)	:	12.7721

Mils Per Year	:	1.4042
Comments	:	AREAS OF ATTACK
Location	:	CORROSION CONTROL INC

Alloy	:	C1010	ID Number	:	06
Initial Weight	:	42.2204	Installed	:	11/1/2006
Final Weight	:	41.4537	Removed	:	3/6/2007
Weight Loss	:	0.7667	Hours Exposed	:	3000
Density (g/cm3)	:	7.8700	Surface Area (in2)	:	12.7721

Mils Per Year	:	1.3592
Comments	:	AREAS OF ATTACK
Location	:	CORROSION CONTROL INC

Alloy	:	C1010	ID Number	:	16
Initial Weight	:	42.5233	Installed	:	11/1/2006
Final Weight	:	41.7678	Removed	:	3/6/2007
Weight Loss	:	0.7555	Hours Exposed	:	3000
Density (g/cm3)	:	7.8700	Surface Area (in2)	:	12.7721

Mils Per Year	:	1.3393
Comments	:	AREAS OF ATTACK
Location	:	CORROSION CONTROL INC

Date: 3/15/2007 Page: 2

Metal Samples,Co., Inc.
Phone: (256) 358-4202
Corrosion Analysis Data Report

Customer : CORROSION CONTROL, INC Shop Order : 99974
Purchase Order: MAIL ORDER

Alloy	:	C1010	ID Number	:	17
Initial Weight	:	42.4908	Installed	:	11/1/2006
Final Weight	:	41.6834	Removed	:	3/6/2007
Weight Loss	:	0.8074	Hours Exposed	:	3000
Density (g/cm3)	:	7.8700	Surface Area (in2)	:	12.7721

Mils Per Year : 1.4313
Comments : AREAS OF ATTACK
Location : CORROSION CONTROL INC

Alloy	:	C1010	ID Number	:	18
Initial Weight	:	42.2072	Installed	:	11/1/2006
Final Weight	:	41.3984	Removed	:	3/6/2007
Weight Loss	:	0.8088	Hours Exposed	:	3000
Density (g/cm3)	:	7.8700	Surface Area (in2)	:	12.7721

Mils Per Year : 1.4338
Comments : AREAS OF ATTACK
Location : CORROSION CONTROL INC

ATTACHMENT NO. 6

COUPON DATA

SIX MONTHS

Date: 5/21/2007 Page: 1

Metal Samples,Co., Inc.
Phone: (256) 358-4202
Corrosion Analysis Data Report

Customer : CORROSION CONTROL, INC Shop Order : 101561
Purchase Order: MAIL ORDER

Alloy	:	C1010	ID Number	:	07
Initial Weight	:	40.9949	Installed	:	11/1/2006
Final Weight	:	39.9206	Removed	:	5/7/2007
Weight Loss	:	1.0743	Hours Exposed	:	4488
Density (g/cm3)	:	7.8700	Surface Area (in2)	:	12.8256

Mils Per Year : 1.2677
Comments : GENERAL OVERALL ATTACK
Location : RACK #1

Alloy	:	C1010	ID Number	:	08
Initial Weight	:	42.1026	Installed	:	11/1/2006
Final Weight	:	41.0820	Removed	:	5/7/2007
Weight Loss	:	1.0206	Hours Exposed	:	4488
Density (g/cm3)	:	7.8700	Surface Area (in2)	:	12.8256

Mils Per Year : 1.2043
Comments : GENERAL OVERALL ATTACK
Location : RACK #1

Alloy	:	C1010	ID Number	:	09
Initial Weight	:	42.2309	Installed	:	11/1/2006
Final Weight	:	41.1994	Removed	:	5/7/2007
Weight Loss	:	1.0315	Hours Exposed	:	4488
Density (g/cm3)	:	7.8700	Surface Area (in2)	:	12.8256

Mils Per Year : 1.2172
Comments : GENERAL OVERALL ATTACK
Location : RACK #1

Alloy	:	C1010	ID Number	:	19
Initial Weight	:	40.5849	Installed	:	11/1/2006
Final Weight	:	39.5224	Removed	:	5/7/2007
Weight Loss	:	1.0625	Hours Exposed	:	4488
Density (g/cm3)	:	7.8700	Surface Area (in2)	:	12.8256

Mils Per Year : 1.2538
Comments : GENERAL OVERALL ATTACK
Location : 2

Date: 5/21/2007 Page: 2

Metal Samples,Co., Inc.
Phone: (256) 358-4202
Corrosion Analysis Data Report

Customer : CORROSION CONTROL, INC Shop Order : 101561
Purchase Order: MAIL ORDER

Alloy	:	C1010	ID Number	:	20
Initial Weight	:	41.7726	Installed	:	11/1/2006
Final Weight	:	40.7222	Removed	:	5/7/2007
Weight Loss	:	1.0504	Hours Exposed	:	4488
Density (g/cm3)	:	7.8700	Surface Area (in2)	:	12.8256

Mils Per Year : 1.2395
Comments : GENERAL OVERALL ATTACK
Location : 2

Alloy	:	C1010	ID Number	:	21
Initial Weight	:	42.2395	Installed	:	11/1/2006
Final Weight	:	41.1844	Removed	:	5/7/2007
Weight Loss	:	1.0551	Hours Exposed	:	4488
Density (g/cm3)	:	7.8700	Surface Area (in2)	:	12.8256

Mils Per Year : 1.2451
Comments : GENERAL OVERALL ATTACK
Location : 2

ATTACHMENT NO. 8

COUPON DATA

EIGHT MONTHS

Date: 7/25/2007 Page: 1

Metal Samples,Co., Inc.
Phone: (256) 358-4202
Corrosion Analysis Data Report

Customer : CORROSION CONTROL, INC Shop Order : 103073
Purchase Order: MAIL ORDER

Alloy	:	C1010	ID Number	:	10
Initial Weight	:	42.4620	Installed	:	11/1/2006
Final Weight	:	41.1730	Removed	:	7/2/2007
Weight Loss	:	1.2890	Hours Exposed	:	5832
Density (g/cm3)	:	7.8700	Surface Area (in2)	:	12.8799
Mils Per Year	:	1.1656			
Comments	:	GENERAL OVERALL ATTACK			
Location	:	RACK #1			

Alloy	:	C1010	ID Number	:	11
Initial Weight	:	42.2906	Installed	:	11/1/2006
Final Weight	:	40.8950	Removed	:	7/2/2007
Weight Loss	:	1.3956	Hours Exposed	:	5832
Density (g/cm3)	:	7.8700	Surface Area (in2)	:	12.8799
Mils Per Year	:	1.2620			
Comments	:	GENERAL OVERALL ATTACK			
Location	:	RACK #1			

Alloy	:	C1010	ID Number	:	12
Initial Weight	:	41.9534	Installed	:	11/1/2006
Final Weight	:	40.5366	Removed	:	7/2/2007
Weight Loss	:	1.4168	Hours Exposed	:	5832
Density (g/cm3)	:	7.8700	Surface Area (in2)	:	12.8799
Mils Per Year	:	1.2812			
Comments	:	GENERAL OVERALL ATTACK			
Location	:	RACK #1			

Alloy	:	C1010	ID Number	:	22
Initial Weight	:	42.5198	Installed	:	11/1/2006
Final Weight	:	41.1866	Removed	:	7/2/2007
Weight Loss	:	1.3332	Hours Exposed	:	5832
Density (g/cm3)	:	7.8700	Surface Area (in2)	:	12.8799
Mils Per Year	:	1.2056			
Comments	:	GENERAL OVERALL ATTACK			
Location	:	RACK #2			

Date: 7/25/2007 Page: 2

Metal Samples,Co., Inc.
Phone: (256) 358-4202
Corrosion Analysis Data Report

Customer : CORROSION CONTROL, INC Shop Order : 103073
Purchase Order: MAIL ORDER

Alloy	:	C1010	ID Number	:	23
Initial Weight	:	42.4141	Installed	:	11/1/2006
Final Weight	:	41.0936	Removed	:	7/2/2007
Weight Loss	:	1.3205	Hours Exposed	:	5832
Density (g/cm3)	:	7.8700	Surface Area (in2)	:	12.8799

Mils Per Year	:	1.1941
Comments	:	GENERAL OVERALL ATTACK
Location	:	RACK #2

Alloy	:	C1010	ID Number	:	24
Initial Weight	:	42.1329	Installed	:	11/1/2006
Final Weight	:	40.7818	Removed	:	7/2/2007
Weight Loss	:	1.3511	Hours Exposed	:	5832
Density (g/cm3)	:	7.8700	Surface Area (in2)	:	12.8799

Mils Per Year	:	1.2218
Comments	:	GENERAL OVERALL ATTACK
Location	:	RACK #2

ATTACHMENT NO. 9

CORROSION PROBE DATA

TWO MONTHS

CORROSION PROBE DATA
BUILDING NO. 125
TORI STATION, OKINAWA
TWO (2) MONTH INSPECTION

PROBE NUMBER	NOV. 13 2006	JAN. 9 2007	NET LOSS MPY
418	55	67	1.53
419	60	70	1.28
420	73	83	1.28
421	66	74	1.02
423	42	59	2.17
424	61	71	1.28

The exposure time was fifty-seven (57) days.

ATTACHMENT NO. 10

CORROSION PROBE DATA

FOUR MONTHS

#762

CORROSION PROBE DATA
BUILDING NO. 125
TORI STATION, OKINAWA
FOUR (4) MONTH INSPECTION

PROBE NUMBER	NOV. 13 2006	MARCH 6 2007	NET LOSS MPY
418	55	73	1.16
419	60	78	1.16
420	73	89	1.03
421	66	78	0.77
423	42	66	1.55
424	61	77	1.03

The exposure time was one hundred thirteen (113) days.

ATTACHMENT NO. 11

CORROSION PROBE DATA

SIX MONTHS

CORROSION PROBE DATA
BUILDING NO. 125
TORI STATION, OKINAWA
SIX (6) MONTH INSPECTION

PROBE NUMBER	NOV. 13 2006	MARCH 6 2007	MAY 2007	NET LOSS MPY
418	55	73	78	0.96
419	60	78	85	1.04
420	73	89	97	1.00
421	66	78	88	0.92
423	42	66	77	1.46
424	61	77	84	0.96

The exposure time was one hundred seventy-five (175) days.

ATTACHMENT NO. 12

CORROSION PROBE DATA

EIGHT MONTHS

CORROSION PROBE DATA
BUILDING NO. 125
TORI STATION, OKINAWA
EIGHT (8) MONTH INSPECTION

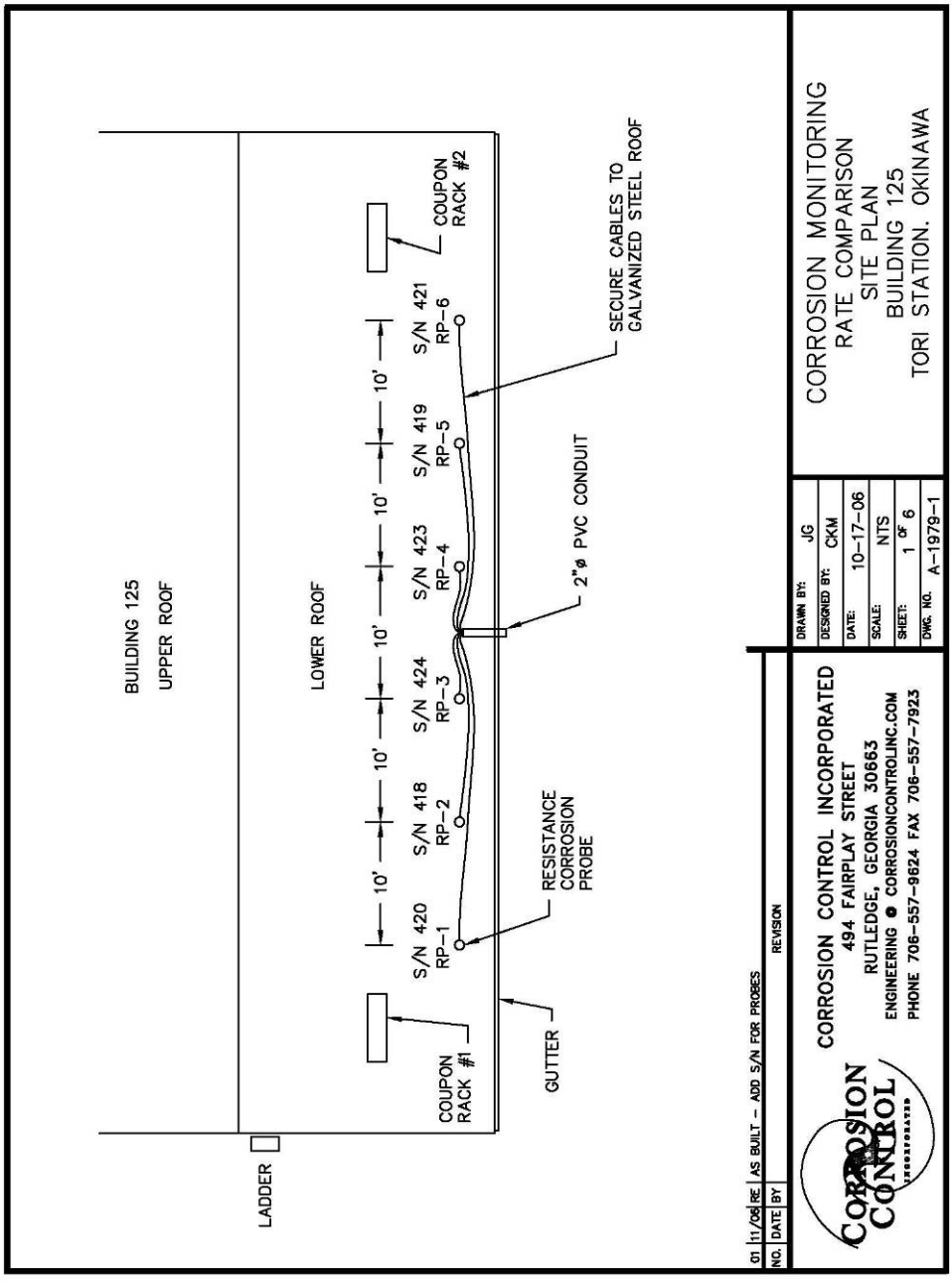
PROBE NUMBER	NOV. 13 2006	MARCH 6 2007	MAY 2007	JULY 2007	NET LOSS MPY
418	55	73	78	88	1.04
419	60	78	85	91	0.98
420	73	89	97	105	1.01
421	66	78	88	95	0.92
423	42	66	77	86	1.39
424	61	77	84	93	1.01

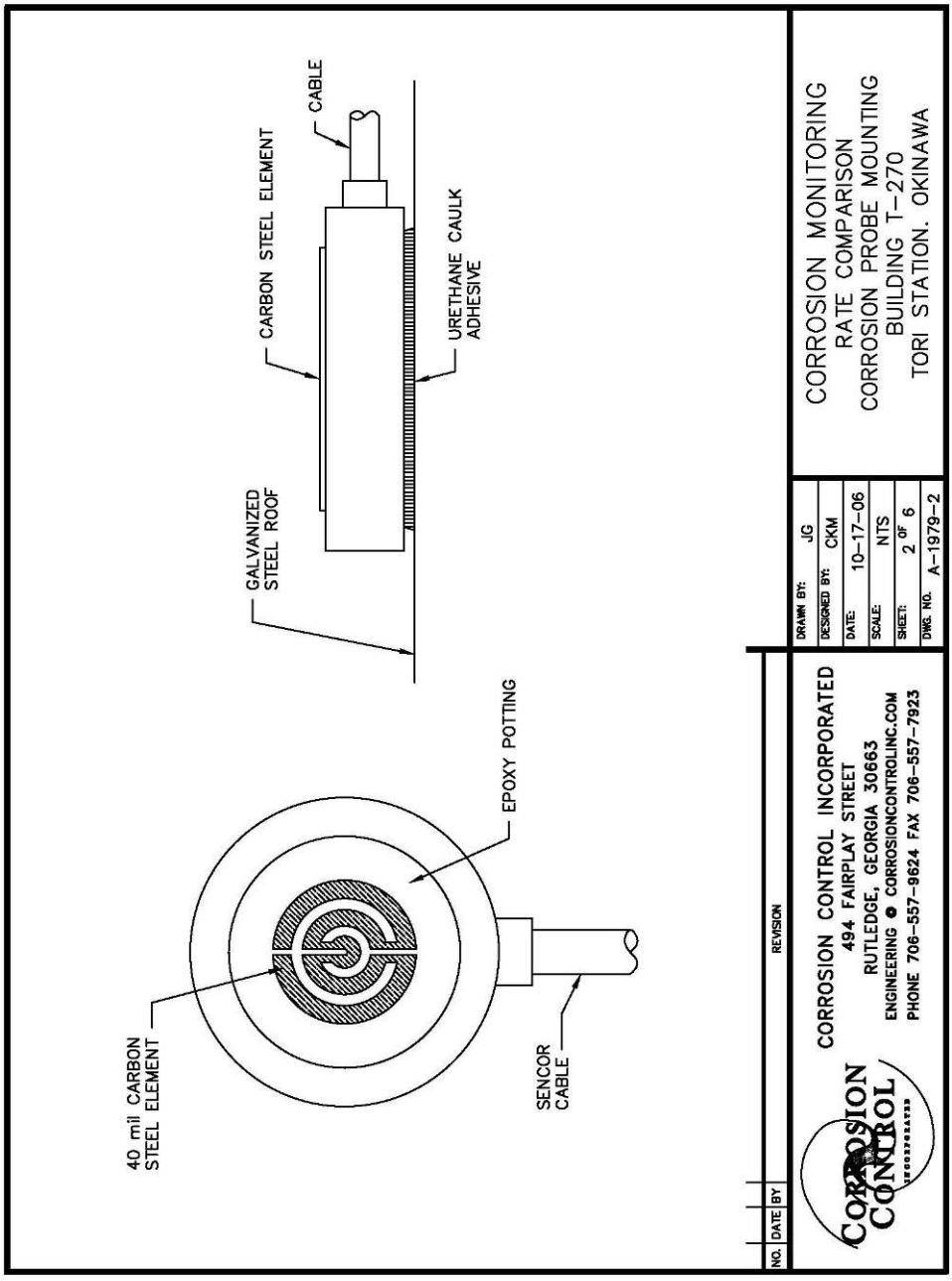
The exposure time was two hundred thirty-one (231) days.

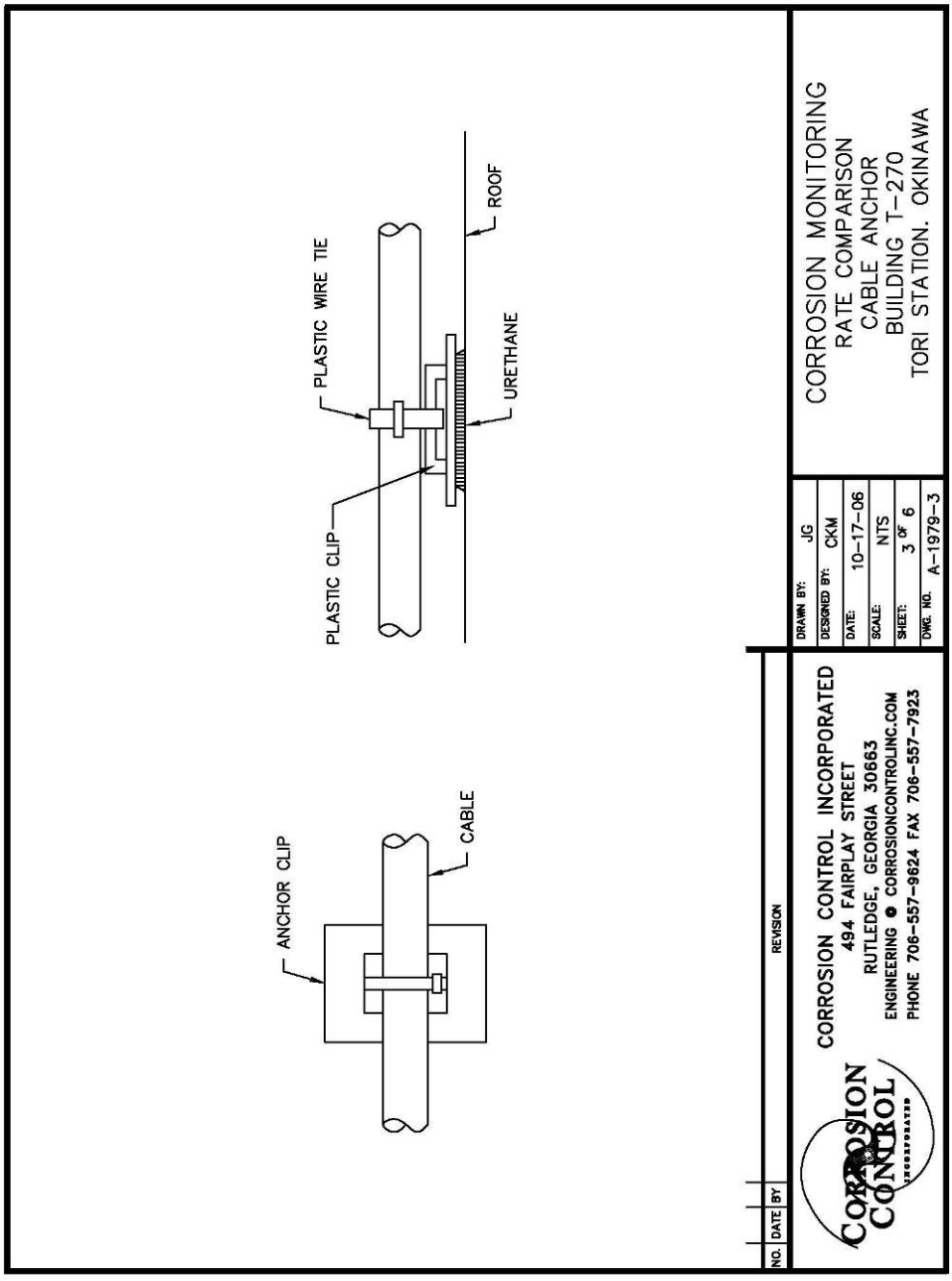
ATTACHMENT NO. 13

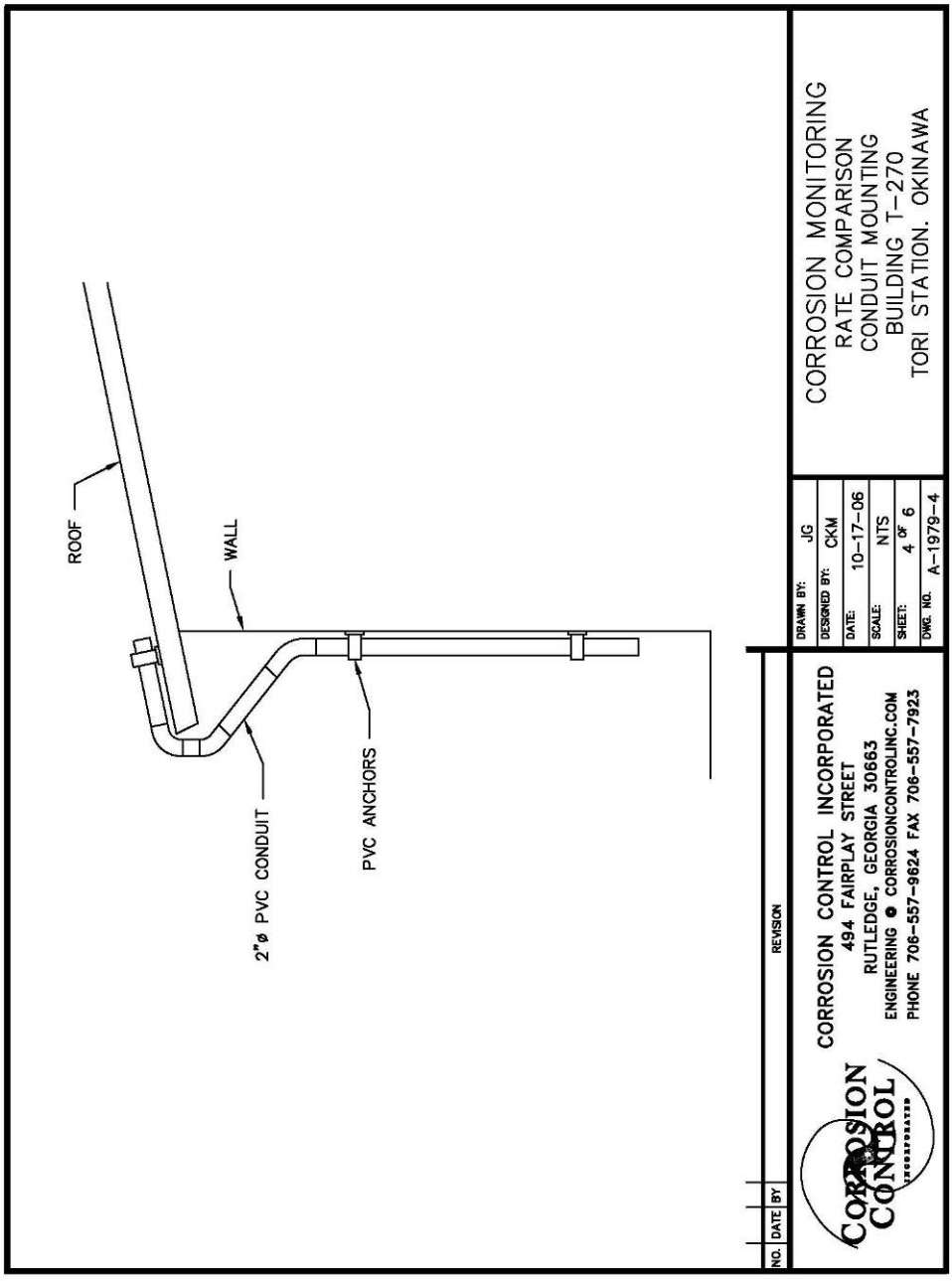
DRAWINGS (A-1979-1/6)

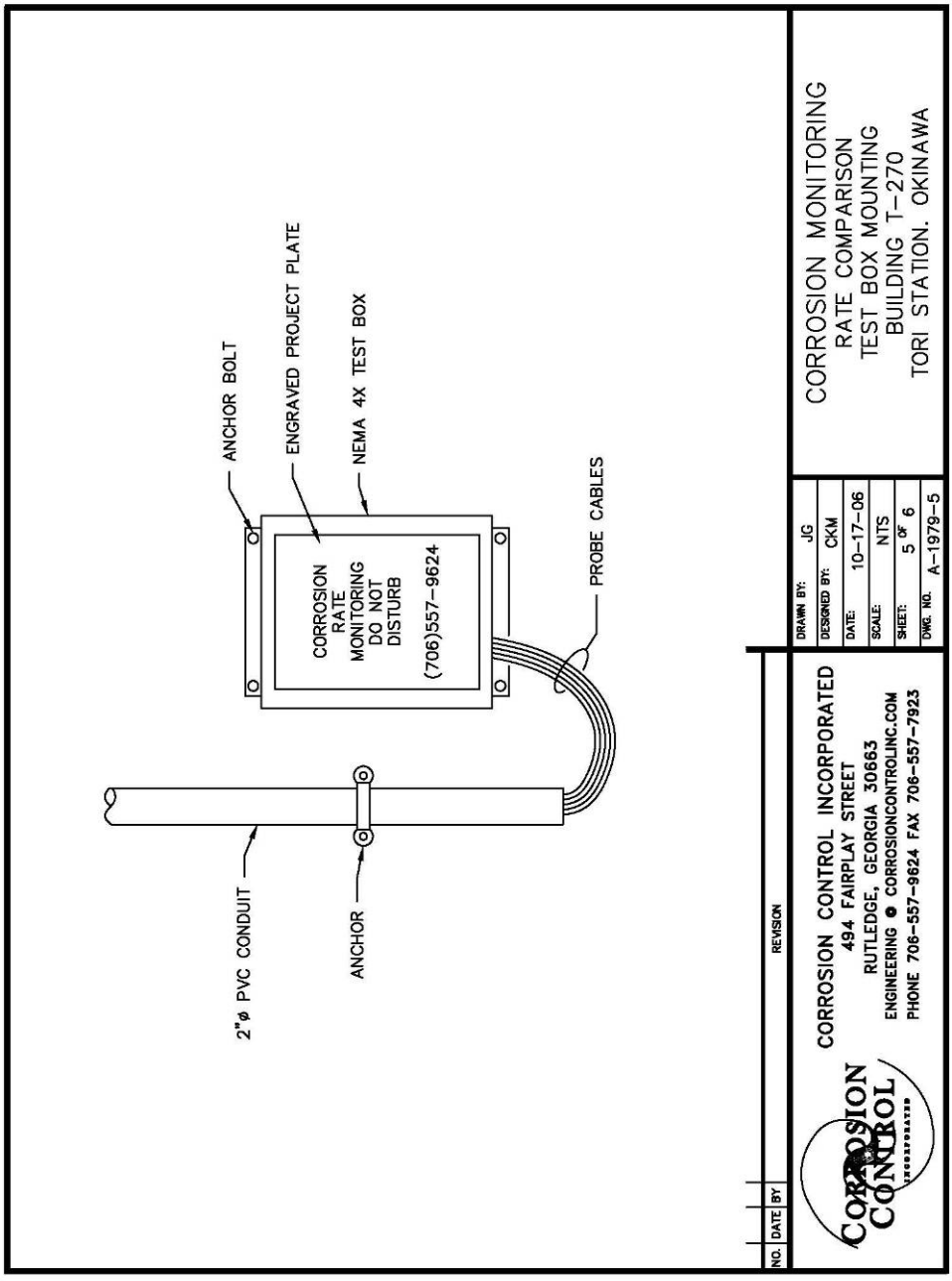
#753

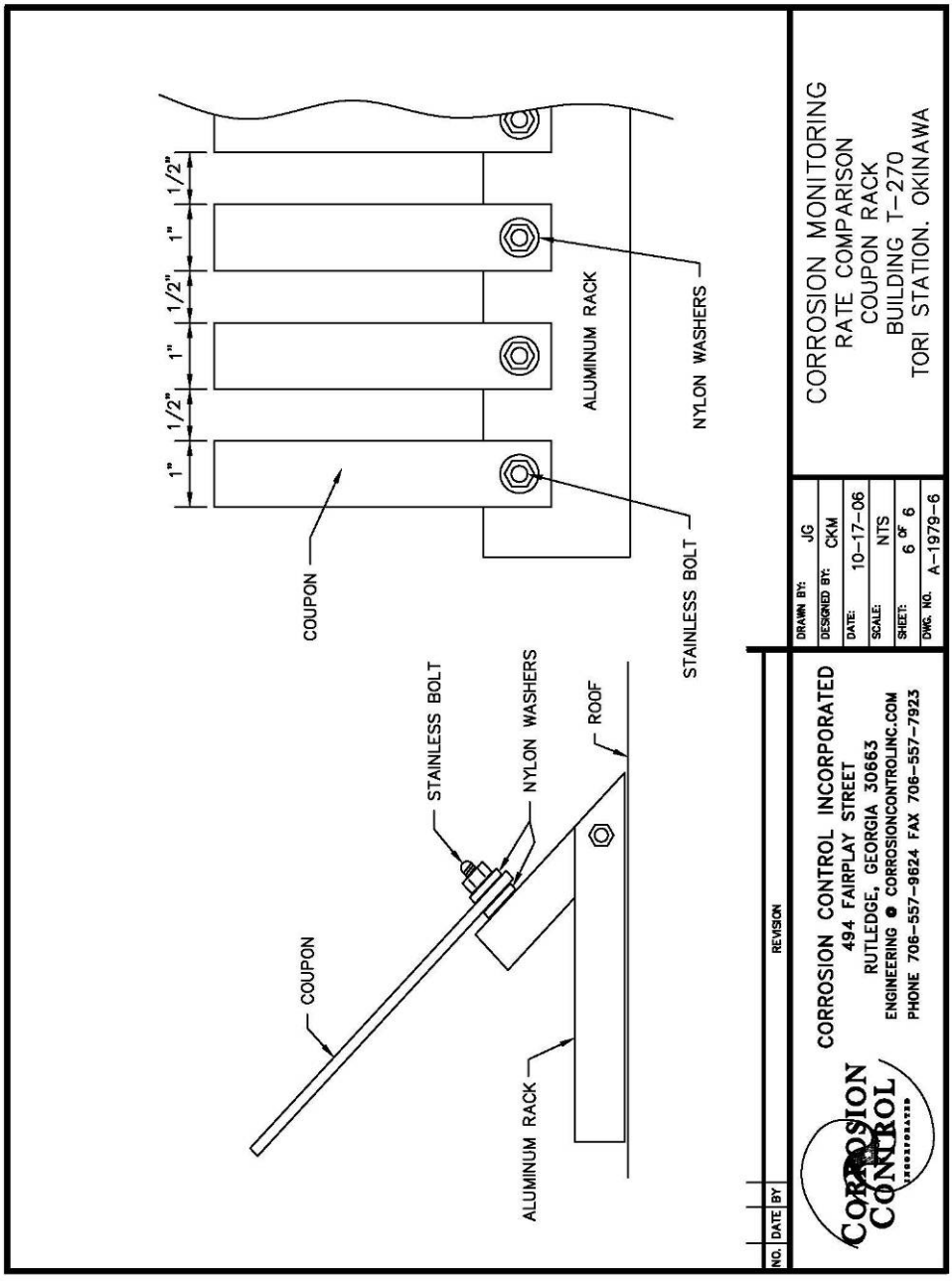

BUILDING 125
UPPER ROOF
LOWER ROOF
LADDER
COUPON RACK #1
COUPON RACK #2
GUTTER
RESISTANCE CORROSION PROBE
2"ø PVC CONDUIT
SECURE CABLES TO GALVANIZED STEEL ROOF
S/N 420 RP-1
S/N 418 RP-2
S/N 424 RP-3
S/N 423 RP-4
S/N 419 RP-5
S/N 421 RP-6
10'
01 11/06 RE AS BUILT - ADD S/N FOR PROBES
NO. DATE BY REVISION
CORROSION CONTROL INCORPORATED
494 FAIRPLAY STREET
RUTLEDGE, GEORGIA 30663
ENGINEERING • CORROSIONCONTROLINC.COM
PHONE 706-557-9624 FAX 706-557-7923
DRAWN BY: JG
DESIGNED BY: CKM
DATE: 10-17-06
SCALE: NTS
SHEET: 1 OF 6
DWG. NO. A-1979-1
CORROSION MONITORING
RATE COMPARISON
SITE PLAN
BUILDING 125
TORI STATION. OKINAWA


CABLE
CARBON STEEL ELEMENT
URETHANE CAULK ADHESIVE
GALVANIZED STEEL ROOF
EPOXY POTTING
40 mil CARBON STEEL ELEMENT
SENCOR CABLE
NO. DATE BY REVISION
CORROSION CONTROL INCORPORATED
494 FAIRPLAY STREET
RUTLEDGE, GEORGIA 30663
ENGINEERING • CORROSIONCONTROLINC.COM
PHONE 706-557-9624 FAX 706-557-7923
CORROSION CONTROL
DRAWN BY: JG
DESIGNED BY: CKM
DATE: 10-17-06
SCALE: NTS
SHEET: 2 OF 6
DWG. NO. A-1979-2
CORROSION MONITORING
RATE COMPARISON
CORROSION PROBE MOUNTING
BUILDING T-270
TORI STATION. OKINAWA


PLASTIC WIRE TIE
ROOF
URETHANE
PLASTIC CLIP
ANCHOR CLIP
CABLE
NO. DATE BY REVISION
CORROSION CONTROL INCORPORATED
494 FAIRPLAY STREET
RUTLEDGE, GEORGIA 30663
ENGINEERING • CORROSIONCONTROLINC.COM
PHONE 706-557-9624 FAX 706-557-7923
DRAWN BY: JG
DESIGNED BY: CKM
DATE: 10-17-06
SCALE: NTS
SHEET: 3 OF 6
DWG. NO. A-1979-3
CORROSION MONITORING
RATE COMPARISON
CABLE ANCHOR
BUILDING T-270
TORI STATION. OKINAWA


ROOF
WALL
2"ø PVC CONDUIT
PVC ANCHORS
NO. DATE BY REVISION
CORROSION CONTROL INCORPORATED
494 FAIRPLAY STREET
RUTLEDGE, GEORGIA 30663
ENGINEERING • CORROSIONCONTROLINC.COM
PHONE 706-557-9624 FAX 706-557-7923
DRAWN BY: JG
DESIGNED BY: CKM
DATE: 10-17-06
SCALE: NTS
SHEET: 4 OF 6
DWG. NO. A-1979-4
CORROSION MONITORING
RATE COMPARISON
CONDUIT MOUNTING
BUILDING T-270
TORI STATION. OKINAWA


ANCHOR BOLT
ENGRAVED PROJECT PLATE
NEMA 4X TEST BOX
CORROSION
RATE
MONITORING
DO NOT
DISTURB
(706)557-9624
PROBE CABLES
2"ø PVC CONDUIT
ANCHOR
NO. DATE BY REVISION
CORROSION CONTROL INCORPORATED
494 FAIRPLAY STREET
RUTLEDGE, GEORGIA 30663
ENGINEERING • CORROSIONCONTROLINC.COM
PHONE 706-557-9624 FAX 706-557-7923
DRAWN BY: JG
DESIGNED BY: CKM
DATE: 10-17-06
SCALE: NTS
SHEET: 5 OF 6
DWG. NO. A-1979-5
CORROSION MONITORING
RATE COMPARISON
TEST BOX MOUNTING
BUILDING T-270
TORI STATION. OKINAWA


1"
1/2"
1"
1/2"
1"
1/2"
COUPON
ALUMINUM RACK
NYLON WASHERS
STAINLESS BOLT
COUPON
STAINLESS BOLT
NYLON WASHERS
ROOF
ALUMINUM RACK
NO. DATE BY REVISION
CORROSION CONTROL INCORPORATED
494 FAIRPLAY STREET
RUTLEDGE, GEORGIA 30663
ENGINEERING • CORROSIONCONTROLINC.COM
PHONE 706-557-9624 FAX 706-557-7923
DRAWN BY: JG
DESIGNED BY: CKM
DATE: 10-17-06
SCALE: NTS
SHEET: 6 OF 6
DWG. NO. A-1979-6
CORROSION MONITORING
RATE COMPARISON
COUPON RACK
BUILDING T-270
TORI STATION, OKINAWA

Appendix F: Atmospheric Corrosion Coupon Tests at Torii Station

QUALITY CONTROL INSPECTIONS FOR CORROSION PREVENTION AND CONTROL PROJECTS (CPC) AT MULTIPLE ARMY INSTALLATIONS

Prime Contract: W9132T-06-D-0001
06T0147 Task; Related Prime Order: 0013

Atmospheric Corrosion Tests at Torii Station, Okinawa, Japan

Draft Final Report

Version 2.00

Prepared for

Mandaree Enterprise Corporation
812 Park Drive
Warner Robins, GA 31088

Prepared by

James B. Bushman and Bopinder Phull

Bushman & Associates
PO Box 425
Medina OH 44256

November 2007

Atmospheric Corrosion Tests at Torii Station, Okinawa, Japan

Background

Due to such close proximity to the ocean, structural materials and appurtenances at Torii Station, Okinawa, are potentially susceptible to severe atmospheric corrosion damage. Such degradation can affect buildings and mission-critical equipment, increase direct maintenance and operational costs, and impact personnel safety. The primary factors contributing to atmospheric corrosion in marine environments include: airborne salt (specifically chloride) transported from the ocean by wind and wave action, time of wetness, high relative humidity, and temperature. Frequent rainfall can have a beneficial effect on boldly exposed (e.g. skyward-facing) surfaces if the chloride is washed off. In contrast, corrosion can be worst on sheltered (e.g. groundward-facing) surfaces not subjected to rain washing. While corrosion typically connotes attack on metallic surfaces, nonmetals can also suffer degradation; for example embrittlement, chalking and cracking of organic coatings and polymeric materials due to UV/solar radiation, swelling associated with water absorption, and so on. Although many advances have been made in conducting corrosion tests on bare metal and coated specimens in the laboratory, the "gold standard" for establishing performance in atmospheric environments continues to be outdoor exposures at representative locations. This approach was also used for evaluating performance of selected systems at Torii Station under Task 6 of this contract.

Bushman & Associates (B&A) was contracted to by Mandaree Enterprise Corporation on behalf of US Army ERDC-CERL (Mandaree-CERL) to prepare and expose two (2) atmospheric test racks containing test panels of the following materials: bare carbon steel, galvanized steel, zinc-rich epoxy-coated steel, phenolic coated steel and bare Type 410 stainless steel.

Preparation and Exposure of Test Panels

B&A used a subcontractor (KTA-Tator, Inc., Pittsburgh, PA) for material acquisition and preparation of test panels of the five aforementioned candidate materials. Replicate test panels of each type were prepared by the vendor. The test panels were nominally 1/8 x 4 x 6 inches. All of the steel panels were A36 steel, grit-blasted to SSPC-SP5 "white metal" finish with

an anchor profile of 2 to 3 mils. For coated panels, the following coating systems were used:

1. Galvanized System - Hot-dip galvanized (Zn coating thickness ~ 3–5 mils).

2. Zinc Rich Primer System - Carboline Carbozinc 859 epoxy zinc primer (3–5 mils) with Carboguard 893SG epoxy topcoat finish (5–7 mils).

3. Phenolic System - Carboline Phenoline 300 primer (8 mils) with Phenoline 302 top coat (8 mils).

The non-coated system used were:

1. Stainless Steel – ASTM Grade 410 with No. 1 mill-finish

2. Carbon Steel – ASTM Grade A-36 with mill-finish

One side of each coated panel was scribed to simulate mechanical damage commonly encountered in service. Each scribe was ~ 4 inches long and ~ 30 mils wide. The scribed side was exposed facing the ocean.

The Type 410 stainless steel panels were exposed in the No. 1 mill-finish condition.

Hot-dip galvanized steel test racks for mounting the panels, porcelain insulators, and associated fasteners were also purchased from KTA-Tator. The test racks and test panels were shipped to Torii Station, Okinawa in December, 2006. B&A mounted the test panels on the racks during its first visit the same month.

CERL had requested that one rack be exposed 100 feet from the ocean and the other 500 feet from the ocean to determine corrosion resistance as a function of distance. It became apparent from B&A's tour of Torii Station and discussions with base personnel that there was no suitable location for exposure at 100-ft. After review with various parties, it was decided to expose the racks in secure areas; one rack ~ 500-ft and the other ~ 2000-ft from the ocean.

Figure 1a – 1c show the test racks mounted on a chain-link fence behind building No. 360, facing the ocean in westerly direction and ~ 500-ft from

it. Figures 2a – 2c show the test racks exposed ~ 2000-ft from the ocean. These racks were mounted on a chain-link fence outside building No. T-113, and also faced the ocean (westerly direction). B&A followed the recommendations of the base personnel at Torri Station regarding the need for very sturdy rack mounting to withstand typhoons that frequently strike Okinawa. Appendix 1 contains a mapsheet of the panels.

Removal and Inspections of Test Panels

Triplicates of each type of panel were removed after the following exposure periods from each exposure location and shipped back to B&A for inspection.

Rack Location	Date exposed	Removal dates	Exposure (days)
~ 500-ft from ocean	12/11/06	2/28/07	79
~ 500-ft from ocean	12/11/06	5/4/07	144
~ 500-ft from ocean	12/11/06	7/12/07	213
~ 500-ft from ocean	12/11/06	8/15/07	247

Racks	Date exposed	Removal dates	Exposure (days)
~ 2000-ft from ocean	12/12/06	2/28/07	78
~ 2000-ft from ocean	12/12/06	5/4/07	143
~ 2000-ft from ocean	12/12/06	7/12/07	212
~ 2000-ft from ocean	12/12/06	8/15/07	246

The test panels were examined visually for overall corrosion resistance/susceptibility; and especially at areas of steel exposed at the scribes. The appearance of unexposed control panels is depicted in Figure 3 for reference; i.e. when making visual comparisons with panels removed from the exposure tests.

Results

1st Removal

Bare steel

The appearance of the bare steel panels from the first removal is shown in Figures 4a – 4d. The panels were completed covered with brown rust. The rust was surprisingly adherent on panels exposed at both locations; no significant difference in the rust was apparent on the front and backsides or as a function of distance from the ocean. The adhesion of the rust may be ascribed to small amounts of copper, often present in A36 steel. Steels capable of generating protective corrosion products in atmospheric environments are known as "weathering" steels.

Galvanized steel

Figures 5a – 5d depict the appearance of the galvanized steel panels. There was no discernible difference between panels removed from both exposure locations; or the front and backsides of the panels. There was no evidence of rust at the scribes, indicating that the steel exposed by the scribe cut through the zinc coating was non-the-less was fully protected galvanic anode action provided by the adjacent zinc affording cathodic protection for the exposed steel.

Zn-rich epoxy-coated steel

The appearance of the Zn-rich epoxy-coated panels is illustrated in Figures 6a – 6d. No differences were observed either between the front and backside; or between the ~500-ft and ~2000-ft exposures. The yellowish/brown color at the scribes signifies incomplete galvanic corrosion protection.

Phenolic epoxy-coated steel

Figures 7a – 7d show the appearance of the phenolic epoxy-coated steel panels. Again, no differences were apparent between the panels from the two exposure locations or between the front and back-

sides. Reddish brown coloration at the scribe indicated corrosion of the steel substrate but there was no evidence of undercutting of the coating. The "bubbles" in the coating on the backside of panel #27 (see Figure 7b) are from the original application and not blisters due to exposure at the test site.

Type 410 Stainless steel

The appearance of the Type 410 stainless steel panels is portrayed in Figures 8a – 8d. The original reflective surface of the panels had changed to a more dull appearance with initiation of localized corrosion leading to rust staining. The most notable difference was the greater degree of localized rusting on the backsides of the panels compared to the front. This is attributed to the following phenomenon:

> Although the front side of the panels is subject to more chloride from the ocean, it also benefits more from the effects of rain washing capable of removing salt deposits. Conversely, the backside of the panels receives less chloride deposition but also less washing by rain.

The difference in corrosion behavior between the ~500-ft and ~2000-ft exposure locations was minimal compared to the difference between the front and backside of the Type 410 stainless steel panels at either location.

2nd Removal

The appearance of the test panels is depicted in Figures 9 – 13. The overall corrosion behavior of the panels was quite similar to that described above for the 1st removals. The rust staining on the front side of the panels exposed at ~500-ft was slightly greater than that at ~2000-ft. The rust staining on the backside of the panels at the two locations was similar but greater than the front side of the panels as discussed earlier.

3rd Removal

Figures 14 – 18 illustrate the appearance of the panels. Again, the overall appearance was quite similar to that described above for the 2nd removal.

4th Removal

The appearance of the final sets of test panels removed from both locations is shown in Figures 19 – 23. The overall appearance was similar to that described above for the 3rd removal. Corrosion of the Type 410 stainless steel panels had progressed slightly more since the 3rd removal.

Corrosion rate of steel

The average thickness of an unexposed steel control panel, determined with the aid of micrometer, was 0.129 inches (SD 0.0005). Representative test panels from the final removals ~500-ft and ~2000-ft exposure locations were chemically cleaned using inhibited HCl (per ASTM Standard G-1) to remove corrosion products; and their average thickness measured to determine corrosion loss. The average thickness of the panel exposed at ~500-ft was 0.126 inches (SD 0.0009); and the panel exposed at ~2000-ft was also 0.126 inches (SD 0.0006). Thus the average thickness loss for each panel was 0.003 inches or 1.5 mils per side in 246 days which corresponds to a corrosion rate of ~2.2 mpy (mils per year).

Discussion

The ~7-month duration of the tests indicated that the corrosion products on the bare steel panels were surprisingly quite protective. This is based on the following factors:

1. The corrosion products were adherent; they were not flaky or easily removed when scratched.
2. Based on thickness loss measurements for the panels exposed for the longest duration (~ 8 months), the corrosion rate at both ~500-ft and ~2000-ft from the ocean was low and similar (~2.2 mpy).
3. While weathering steels (e.g. copper-containing A36) find considerable application in many mild atmospheres, extreme caution is necessary when considering their use in marine atmospheres.
4. High chloride deposit concentration and long times of wetness increase the risk of not developing sufficiently protective corrosion products.
5. As discussed previously, frequent rainfall can be beneficial in reducing chloride deposits. However, this only applies to boldly exposed surfaces. Sheltered surfaces where chloride deposition occurs but which do not benefit from rain washing can incur considerably

higher rates of corrosion. Such surfaces would need to be protected, e.g. with coatings.

6. If weathering steels are to be considered for use at Torii station, it is essential to conduct long-term tests, e.g. 2 years or longer. Also, the several locations at Torii Station should be characterized, e.g. for chloride deposition by ASTM Standard G-140[1] "wet candle" method; and rapid corrosivity assessment (via % mass loss) by wire-on-bolt method[2].

Galvanized steel exhibited good performance with complete protection at the scribe areas since no red rust was observed. Historically, galvanized steel has been found to provide good protection to steel in marine environments. The mechanism of protection is often attributed to a combination of barrier and sacrificial properties. The life of the galvanized coating is related to the local environment and original coating thickness. The consumption rate of the coating is usually determined from average loss of Zn on test specimens exposed to the atmosphere. It has been shown[3] that skyward-facing side of zinc-coated test specimens incurs considerably more corrosion than the groundward-facing side – attributed to removal of protective corrosion products by rain washing (this is opposite to the case for case for weathering steels where the groundward-facing side often suffers from more corrosion due to lack of rain washing). Thus, the average Zn-metal loss determination overestimates the life of the galvanized coating. In unpolluted marine environments the consumption rate of the coating is estimated to be ~ 0.15 mpy. In polluted marine environments, the consumption rate may be increased by the factor of 2 to 3. Galvanized coatings are a good candidate for protection of steel in the atmosphere at Torii Station. However, sufficient coating thickness is necessary to obtain long life. For components and structures that cannot be hot-dip galvanized, thermal spraying (metallizing) is a very attractive method, especially in field applications. Thermal sprayed coatings of Zn, 6-mils thick, have been shown to provide 50+ years life in unpolluted aggressive marine environments.[4]

The zinc-rich coating evaluated in this program exhibited slight loss of gloss but provided good protection to the steel where the coating was undamaged. However, at scribed areas, which represented simulated coating damage, rust coloration was observed even on the 1st set of panels removed after ~ 2 months' exposure; there was undercutting of the coating system. The galvanic protection provided by the zinc-rich coating was incomplete compared to the hot-dip galvanized coating. Zinc-rich primers topcoated

with a non-conductive coating have been reported[5] to interfere with sacrificial action of the zinc although the mechanism has yet to be elucidated. Long-term testing is essential to compare the performance of a zinc-rich primer, with and without a topcoat, to determine suitability of such coating systems at Torii Station. Without further testing, this coating system should not be considered for use at Torii Station.

The overall performance of the phenolic-epoxy coating was good although there was slight reduction in gloss. Red rust at the scribed areas indicated corrosion; however, no undercutting of the coating was evident. Damaged areas would need to be protected in service, e.g. by touch-up maintenance painting as needed, say, during yearly inspections. Again, long-term testing is necessary to determine the suitability of a phenolic-epoxy coating at Torii Station. This coating system cannot be recommended on the basis of satisfactory performance in the ~8-month test conducted in the present program.

The localized corrosion and rust staining of the Type 410 stainless steel panels exposed at Torii Station was not surprising. Type 410 is a martensitic Fe-Cr alloy (UNS S41000) containing ~ 11.5 % Cr. This lean composition means that its corrosion resistance in aggressive marine environments is very low. After a number of years exposure, it has the appearance of rusty carbon steel. However, unlike carbon steel, the corrosion products on Type 410 stainless steel are generally not as voluminous and thus are less likely to cause “pillowing”. Pillowing can induce large stresses on adjacent surfaces due to expansion associated with voluminous corrosion products. Martensitic stainless steels are susceptible to pitting and chloride stress corrosion cracking in marine atmospheres. They are also prone to hydrogen embrittlement in marine atmospheric applications where electrical contact with active metals, e.g. Al, Zn, or Cd is present. A 26-year exposure study[6] reported the following data for Type 410 stainless steel panels at Kure Beach, NC: (i) pit depths ~2 mils and ~0.4 mils deep on bold surfaces exposed at 80-ft and 800-ft from the ocean, respectively; (ii) crevice corrosion depths of ~8 mils and ~6 mils deep at spot-welded lap joints on panels exposed at 80-ft and 800-ft from the ocean, respectively.

Although many other grades of stainless steel with higher alloying additions are more resistant than Type 410, they are not immune to corrosion in aggressive marine atmospheres over long exposure times unless they are kept clean. For example, 18/8 or 300-series (e.g. Type 304 and 316)

which are sometimes referred to as "marine" grades can incur pitting and staining[6]. The following corrosion data were reported[6] for panels exposed for 26 years at Kure Breach, NC: (i) Type 304 – bold surface pit depths < 0.4 mils deep on panels exposed at 80-ft and 800-ft from the ocean, respectively; (ii) crevice corrosion depths of ~4 mils and ~2 mils at 80-ft and 800-ft from the ocean, respectively; (iii) Type 316 – bold surface pits < 0.4 mils deep at 80-ft and 800-ft from the ocean, respectively; (iv) crevice corrosion depths of ~6 mils and <0.4 mils at 80-ft and 800-ft from the ocean, respectively. Without cleaning, surfaces subjected to chloride deposition will stain during prolonged exposures. However, staining does not necessarily represent failure. Thus, functionality can still exist even though the material may no longer be "stainless" in appearance. Stainless steels with very high resistance to marine atmospheres include 6%-Mo-containing austenitic grades (e.g. AL-6XN, 254 SMO, 20Mo-6), duplex grades (e.g. 2507), and ferritic grades (e.g. 29-4C). All of these grades also have high resistance to chloride stress corrosion cracking. One caveat about stainless steel fasteners is their propensity to galling. A suitable lubricant or coating can alleviate this problem.

Conclusions

The following conclusions can be drawn from the ~7-month marine atmospheric exposure program on candidate material at Torii Station.

1. A-36 steel appeared to develop protective corrosion products, exhibiting behavior similar to that of weathering steels. Based non average thickness loss measurements, the corrosion rate of steel was ~ 2.2 mpy, both ~ 500-ft and ~ 2000-ft from the ocean.

2. Hot-dip galvanized coating exhibited good performance, including complete protection (by sacrificial action) at scribed areas that simulated mechanical damage to the coating. This coating is an excellent choice for Torii Station provided sufficient coating thickness is used for long life. To assure that the desired coating thickness is provided by vendors, it is paramount that the required surface preparation and minimum zinc coating thickness be specified and then tested on all products delivered for use at Torii Station. Without both steps, poor quality and too thin zinc coating will almost surely be provided on occasion. The instrumentation necessary to test this thickness costs typically $200 to $500 and can be used without any specialized training.

3. A zinc-rich primer coating with an epoxy topcoat provided good protection overall; but sacrificial protection at scribed areas was incomplete.

4. A phenolic-epoxy coating provided good protection overall; but there was no protection at scribed areas.

5. There was no undercutting of the coating systems tested.

6. Type 410 stainless steel exhibited localized corrosion and rust staining within the first few months of exposure. Corrosion on the backside was greater than the front side of the panels. Exposure at ~500-ft was not significantly greater than at ~2000-ft. This material is not considered suitable for marine atmospheric applications.

7. Long-term testing, e.g. 2 years or more is essential, to establish suitability of candidate coating systems for use at Torii Station. The resulting data can then be incorporated into the Materials Selection Guide.

References

1. ASTM G-140: Standard Method for Determining Atmospheric Chloride Deposition Rate by Wet Candle Method, ASTM International, Vol. 03.02, 2002.

2. D.P. Doyle and T.E. Wright, Rapid Methods For Determining Atmospheric Corrosivity and Corrosion Resistance, in Atmospheric Corrosion, W.H. Ailor, editor; John Wiley and Sons, 1982.

3. H. E. Townsend, Atmospheric Corrosion of Skyward- and Groundward-Exposed Surfaces of Zinc- and 55% Al-Zn-Coated Steel Sheet, Corrosion 54, (7), 1998, pp 561-565, NACE International, Houston, TX.

4. B. S. Phull, R. M. Kain and S. J. Pikul, Long-Term Marine Atmospheric Corrosion Experiences, Paper No. 07237 Corrosion/2007, NACE International.

5. Ken Tator, private communication.

6. E. A. Baker and T. S. Lee, "Long-Term Atmospheric Corrosion Behavior of Various Grades of Stainless Steel", in *Degradation of Metals* in *the Atmosphere*, ASTM STP 965, S. W. Dean and T. S. Lee, editors, ASTM International, 1988.



Figure 1a – View of location behind building No. 300 where one set of test racks was exposed ~500-ft from the ocean



Figure 1b – View of racks exposed at ~500-ft location (another rack was exposed to the right – not in view).



Figure 2a – View of location outside building No. T-113 where second set of test racks was exposed ~2000-ft from the ocean



Figure 2b – Closer view of racks exposed at ~2000-ft location



Figure 3 – Unexposed controls

- Top Row: Left – grit-blasted bare carbon steel, Center – hot-dip galvanized steel, Right – Zn-rich primer with epoxy topcoat.
- Bottom row: Left – phenolic epoxy, Right – Type 410 stainless steel.

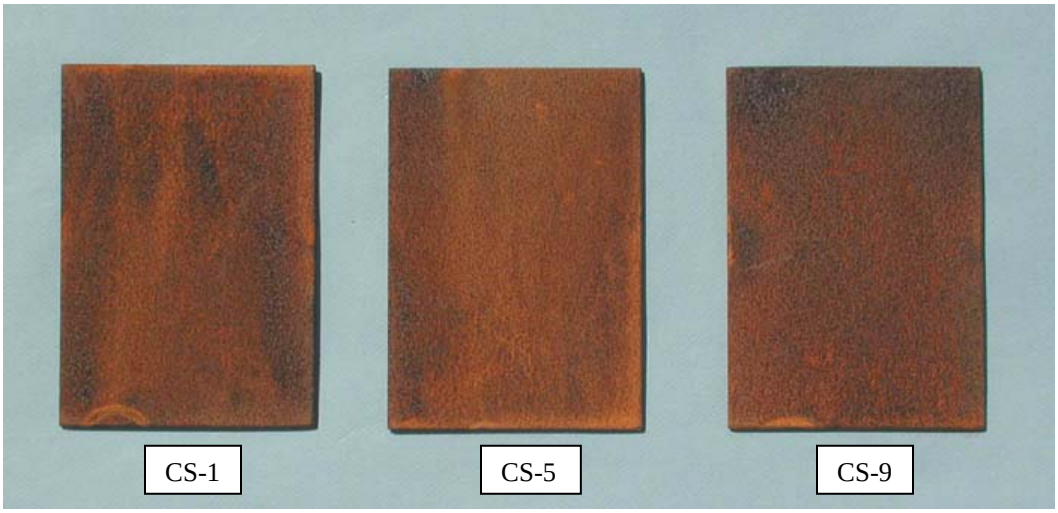


Figure 4a – Carbon steel: 1st removal (79 days); ~500-ft, front face

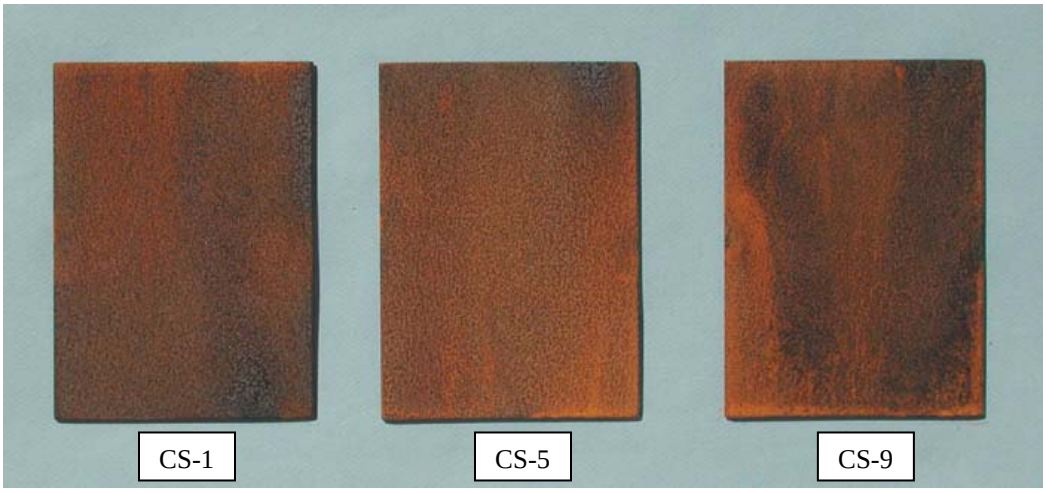


Figure 4b – Carbon steel: 1st removal (79 days); ~500-ft, backside

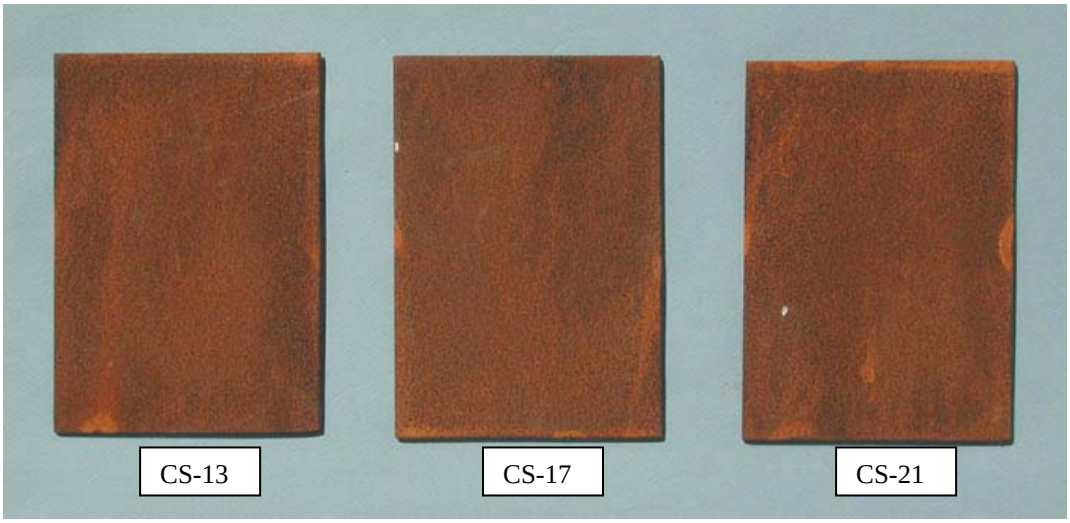


Figure 4c – Carbon steel: 1st removal (78 days); ~2000-ft, front face

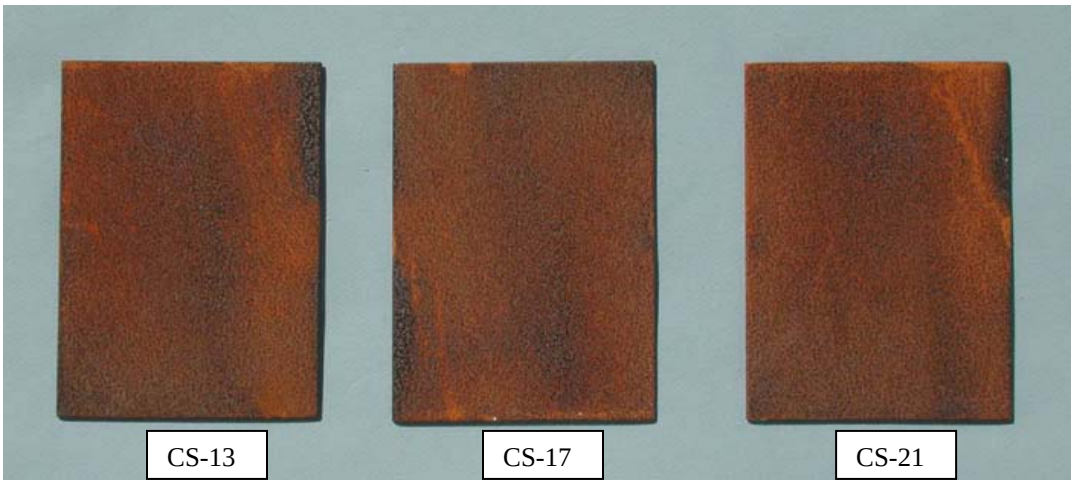


Figure 4d – Carbon steel, 1st removal (78 days); ~2000-ft, backside

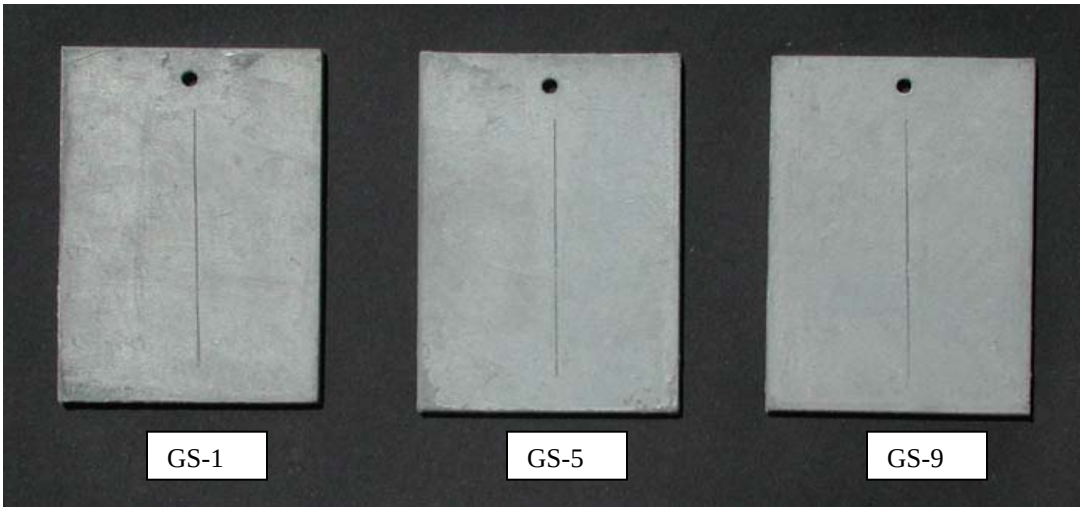


Figure 5a – Galvanized steel, 1st removal (79 days); ~500-ft, front face

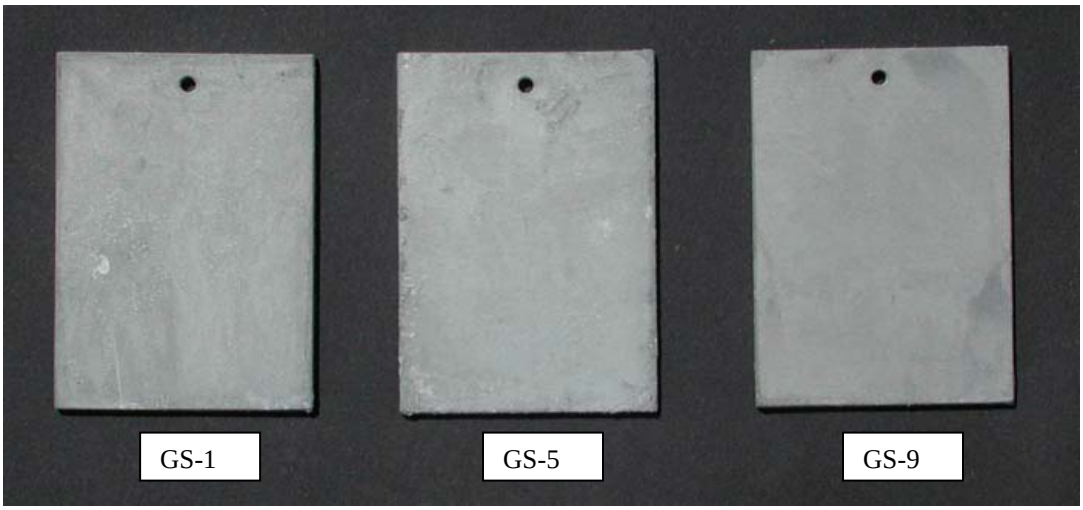


Figure 5b – Galvanized steel, 1st removal (79 days); ~500-ft, backside

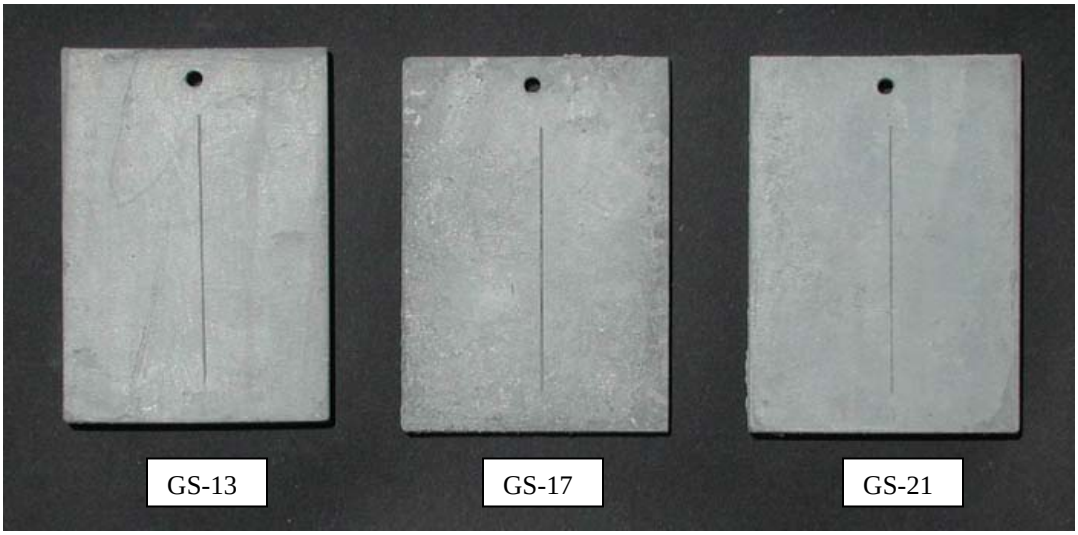


Figure 5c – Galvanized steel, 1st removal (78 days); ~2000-ft, front face

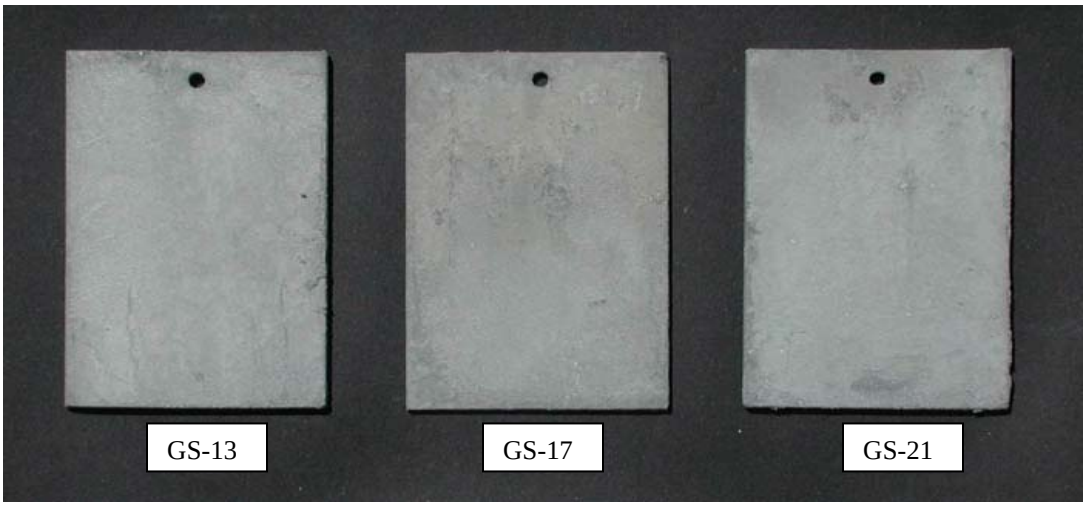


Figure 5d – Galvanized steel, 1st removal (78 days); 2000-ft, backside

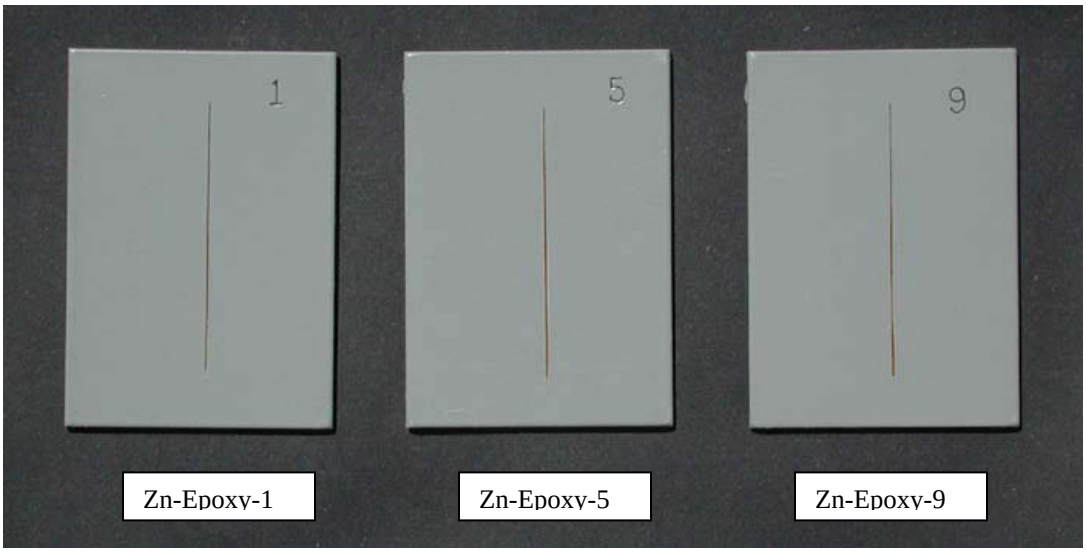


Figure 6a – Zn-epoxy coated steel, 1st removal (79 days); 500-ft, front face

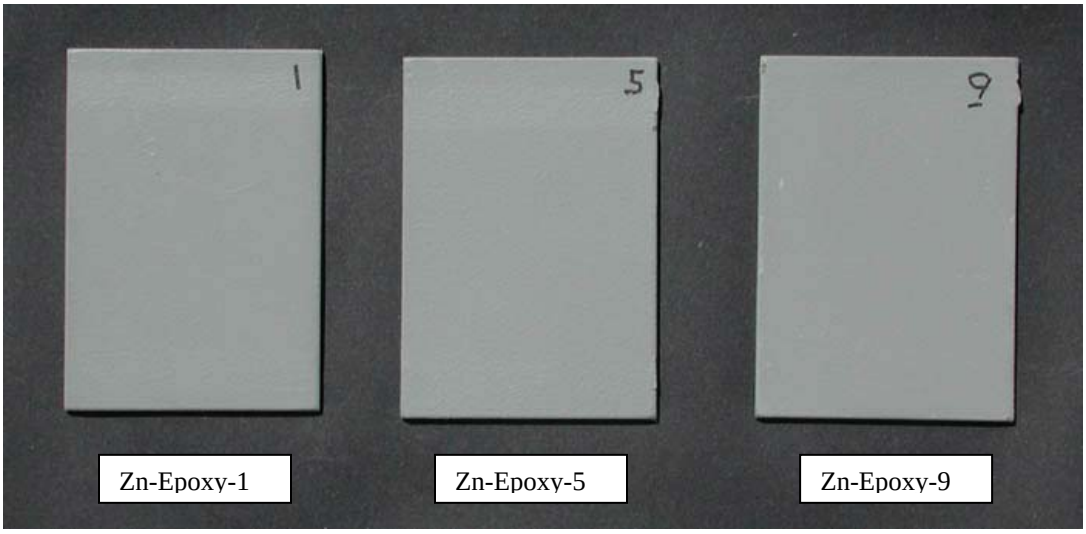


Figure 6b – Zn-epoxy coated steel, 1st removal (79 days), 500-ft, backside

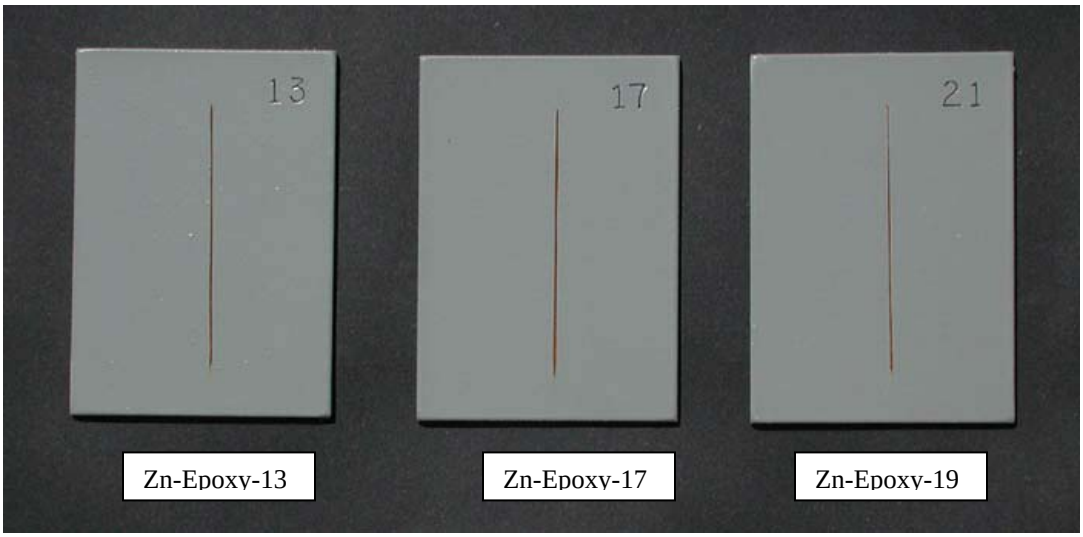


Figure 6c – Zn-epoxy coated steel, 1st removal (78 days); 2000-ft, front face

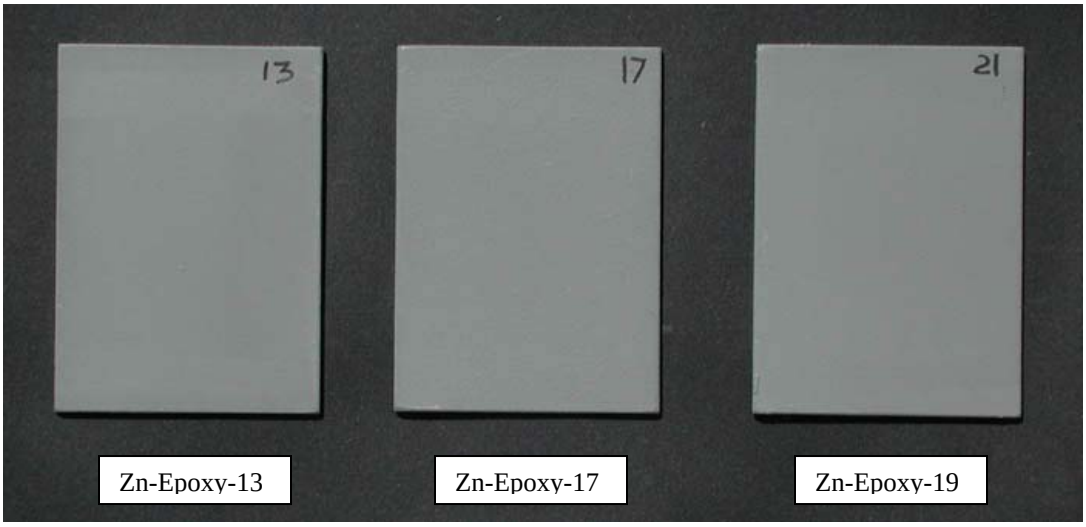


Figure 6d – Zn-epoxy coated steel, 1st removal (78 days); 2000-ft, backside

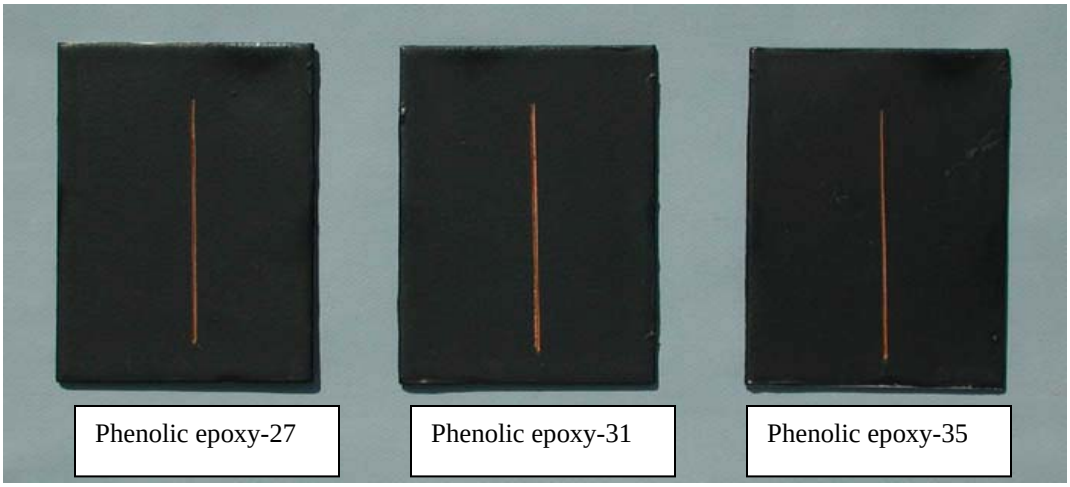


Figure 7a – Phenolic-epoxy coated steel, 1st removal (79 days); 500-ft, front face

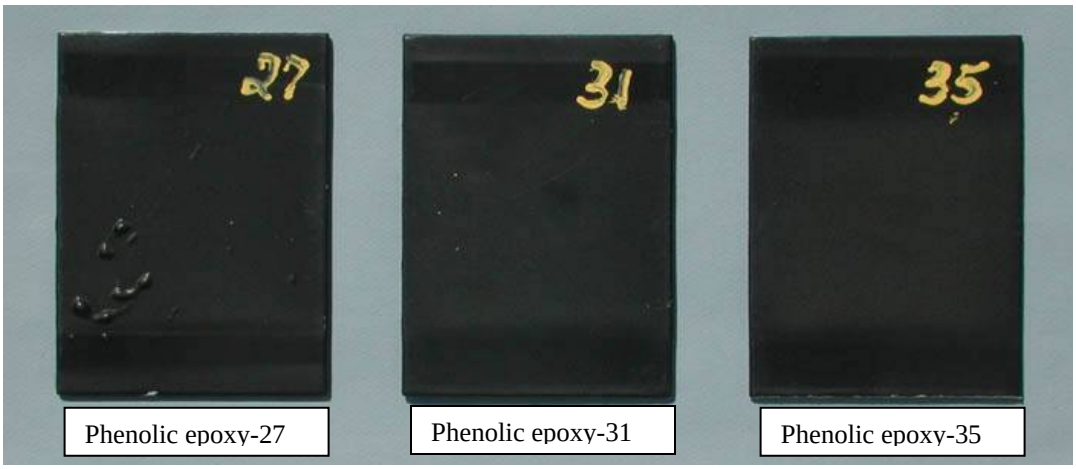


Figure 7b – Phenolic-epoxy coated steel, 1st removal (79 days); 500-ft, backside; the "bubbles" in the coating on panel #27 are drips from the original application and blisters due to coating deterioration

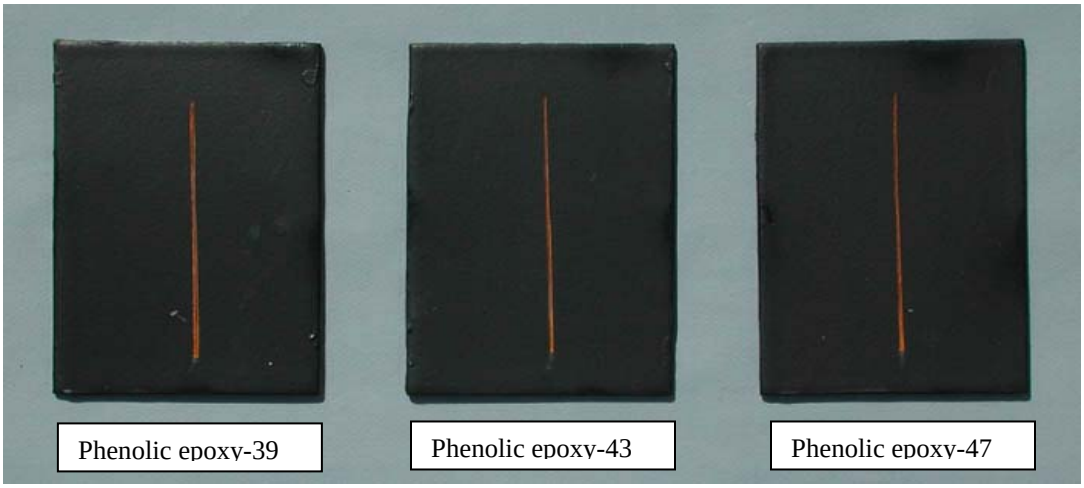


Figure 7c – Phenolic epoxy coated steel, 1st removal (78 days); 2000-ft, front face

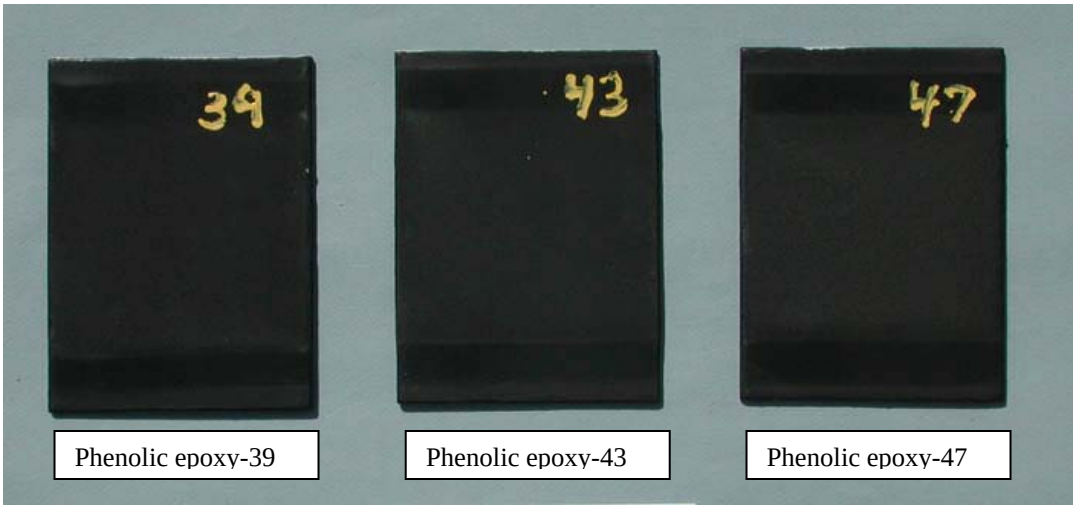


Figure 7d – Phenolic epoxy coated steel, 1st removal (78 days); 2000-ft, backside

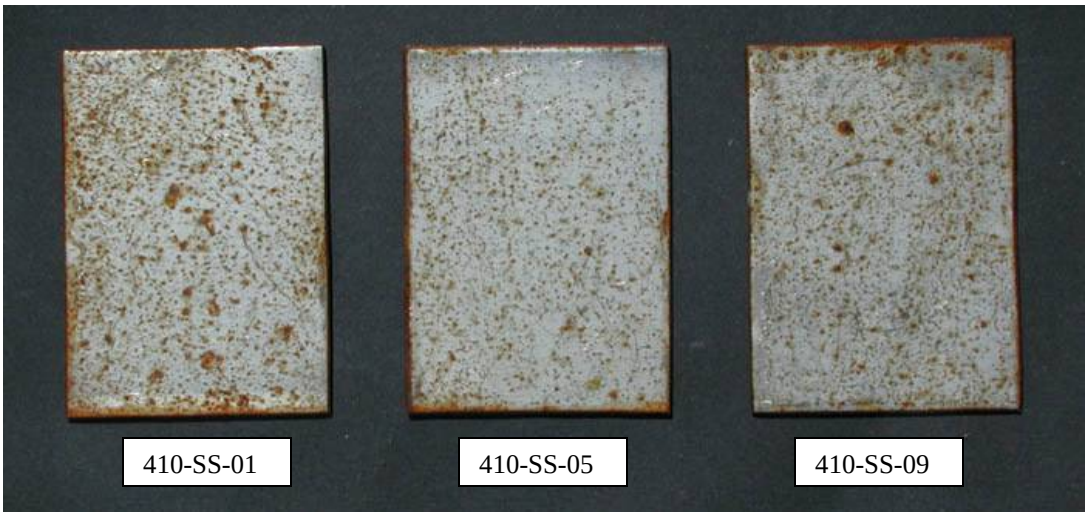


Figure 8a – Type 410 Stainless steel, 1st removal (79 days); 500-ft, front face

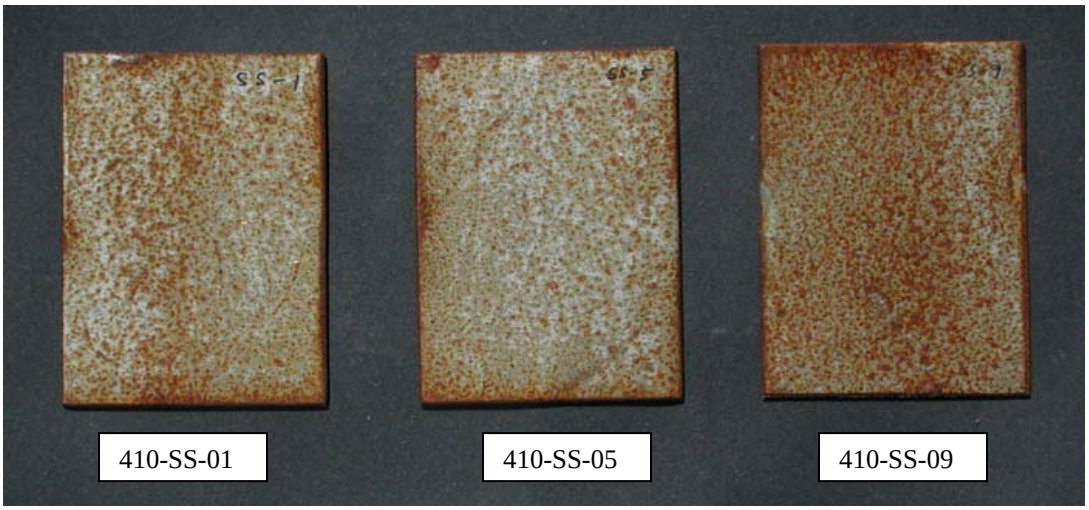


Figure 8b – Type 410 Stainless steel, 1st removal (79 days); 500-ft, backside

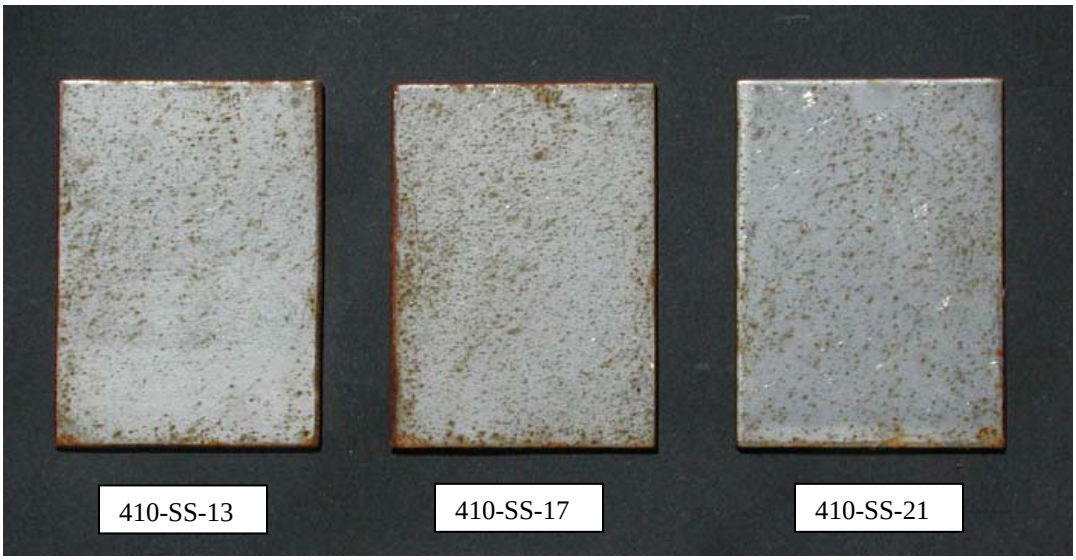


Figure 8c – Type 410 Stainless steel, 1st removal (78 days); 2000-ft, front face

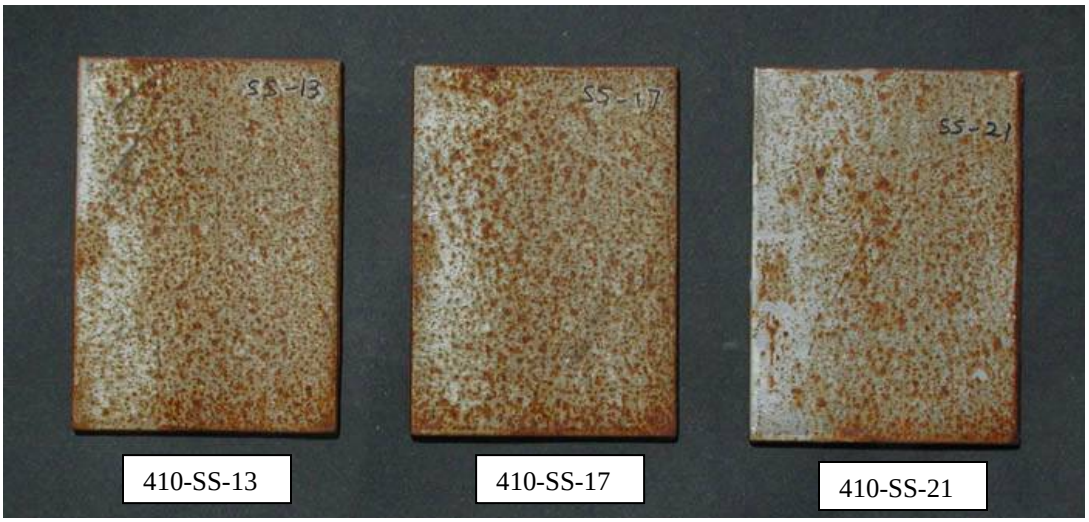


Figure 8d – Type 410 Stainless steel, 1st removal (78 days); 2000-ft, backside

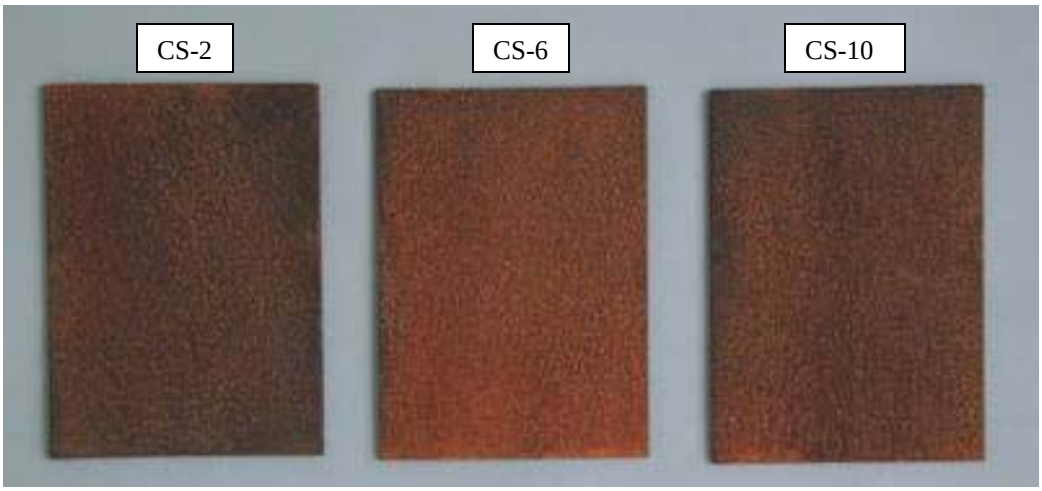


Figure 9a – Carbon steel, 2nd removal (144 days); ~500-ft, front face

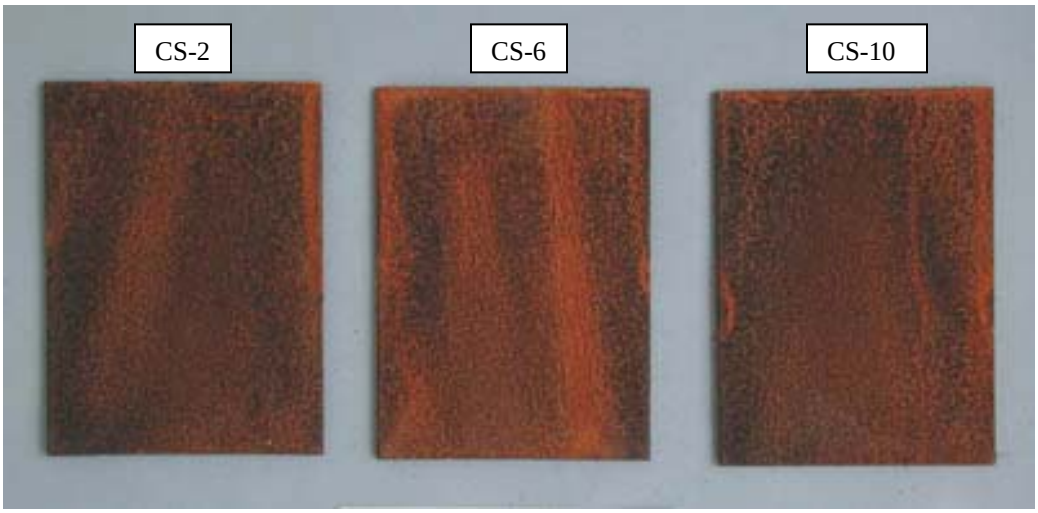


Figure 9b – Carbon steel, 2nd removal (144 days); 500-ft, backside

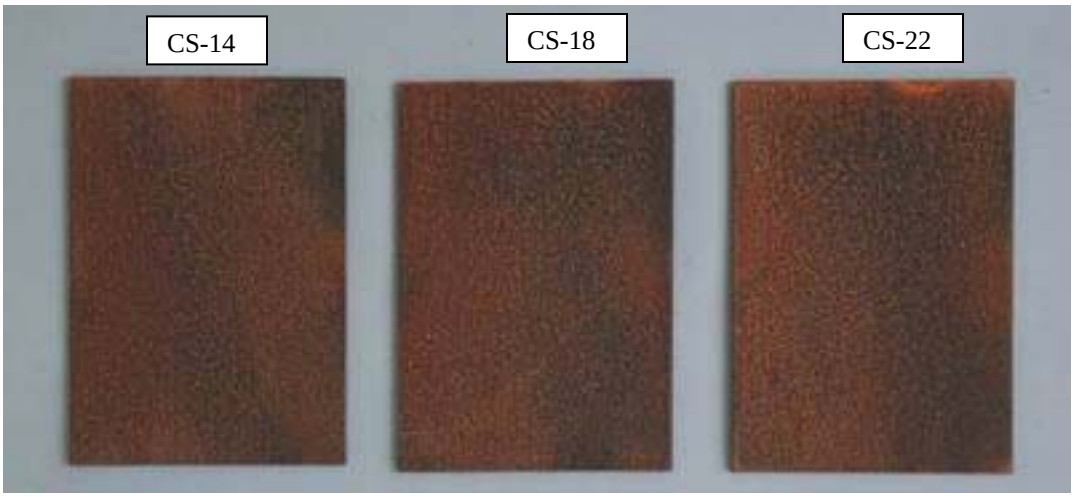


Figure 9c - Carbon steel, 2nd removal (143 days); ~2000-ft, front side

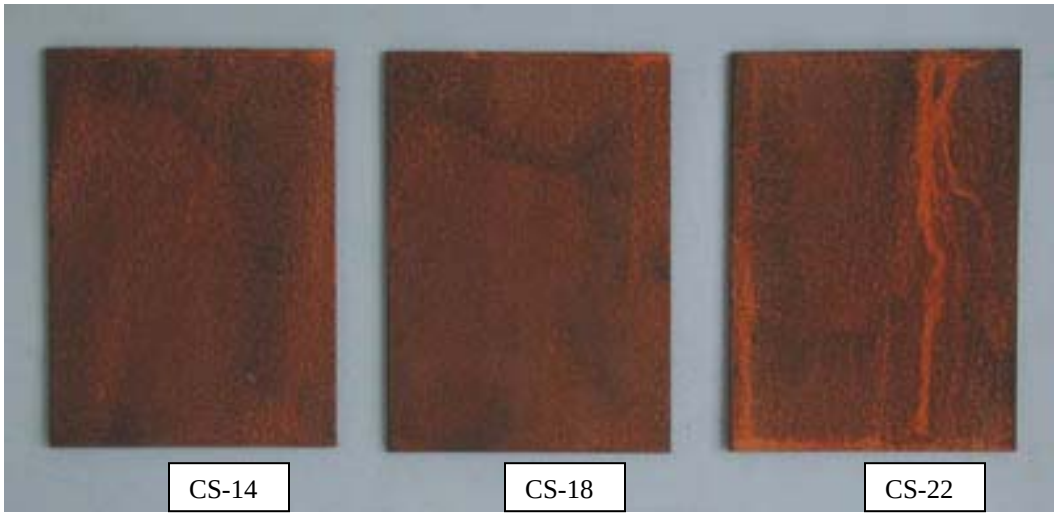


Figure 9d - Carbon steel, 2nd removal (143 days); ~2000-ft, backside

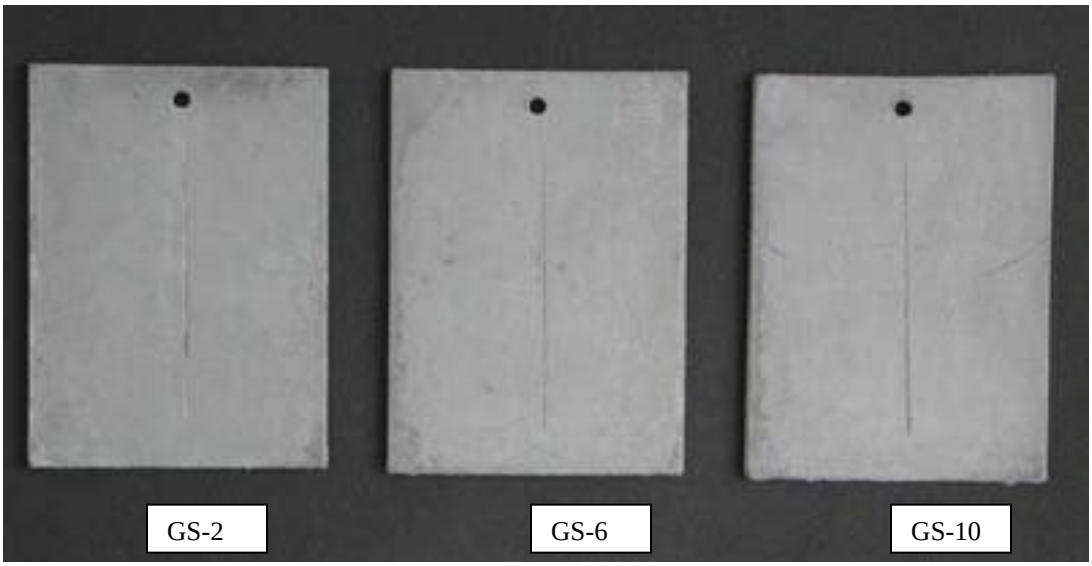


Figure 10a - Galvanized steel, 2nd removal (144 days); ~500-ft, front face

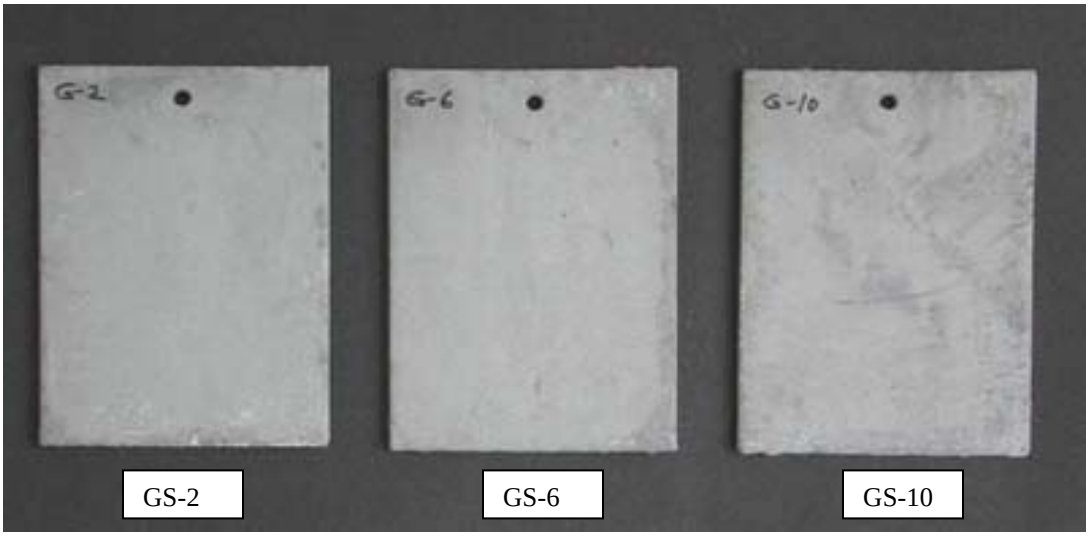


Figure 10b – Galvanized steel, 2nd removal (144 days); ~500-ft, backside

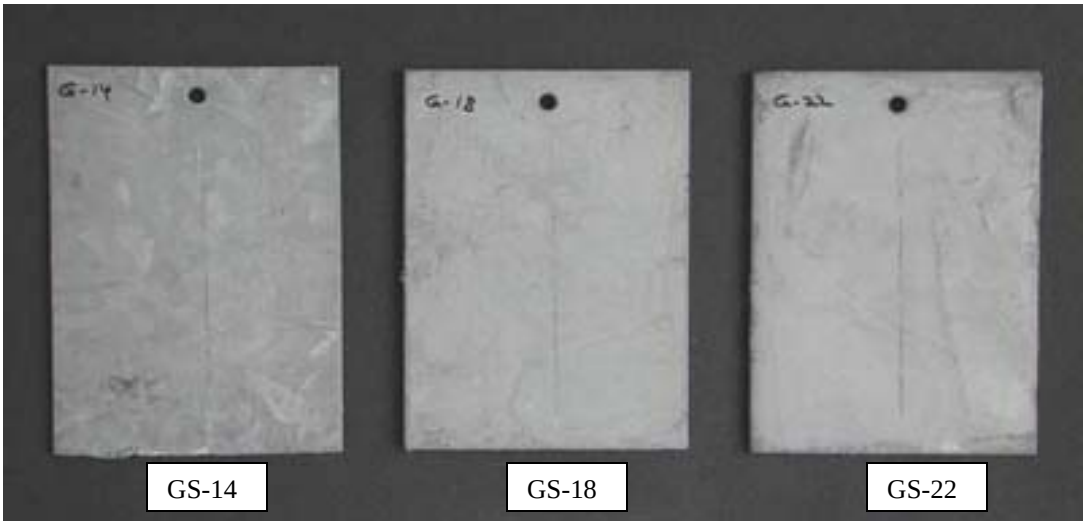


Figure 10c – Galvanized steel, 2nd removal (143 days); ~2000-ft, front face

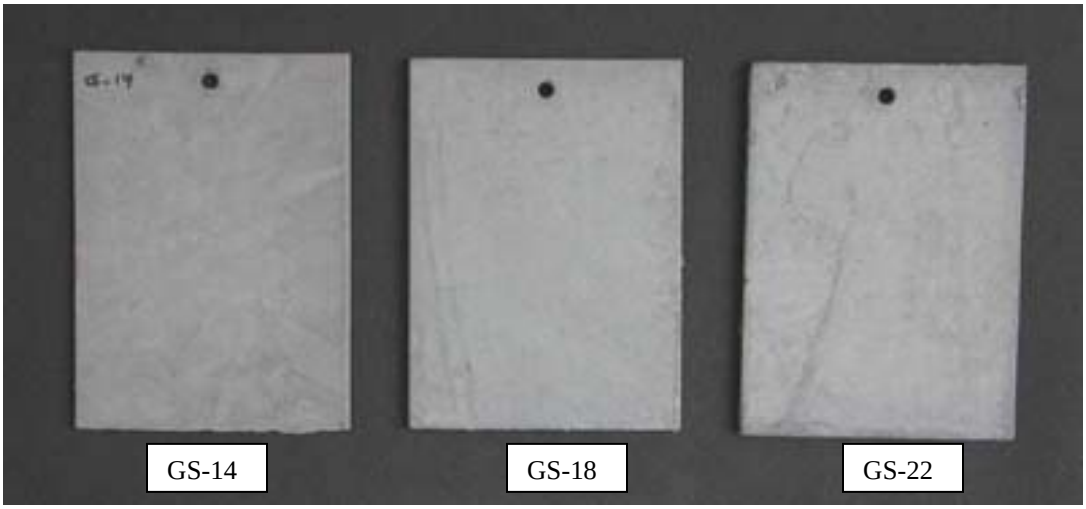


Figure 10d – Galvanized steel, 2nd removal (143 days); ~2000-ft, backside

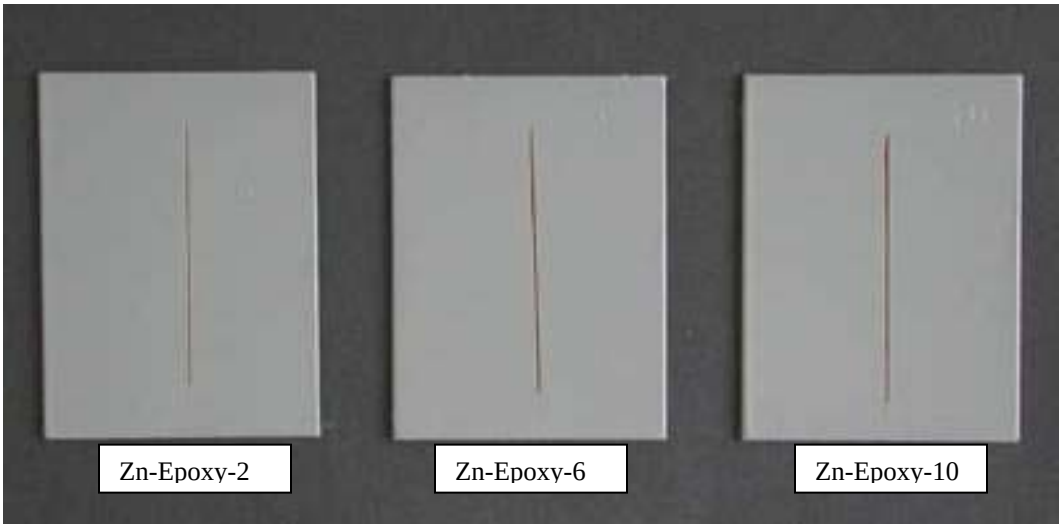


Figure 11a – Zn-epoxy coated steel, 2nd removal (144 days); ~500-ft, front face

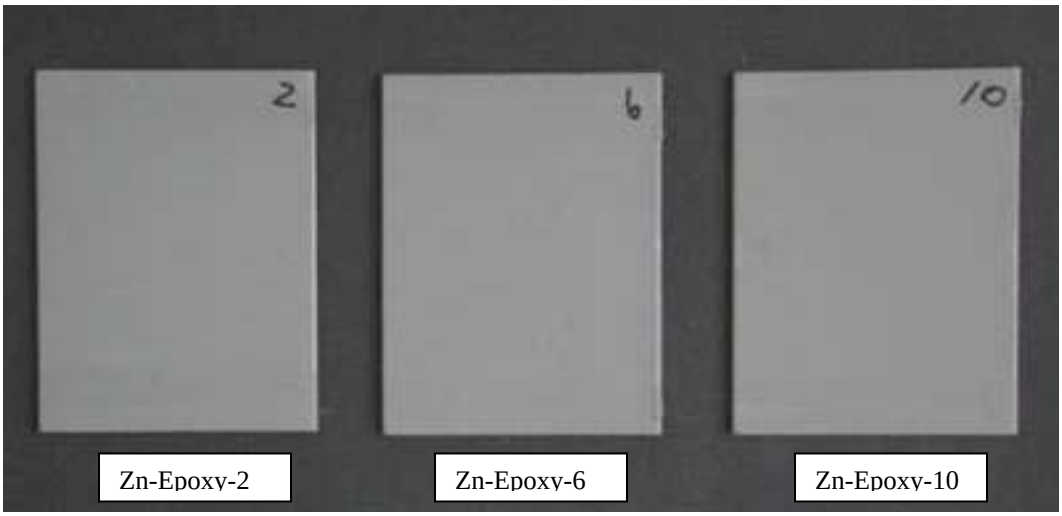


Figure 11b – Zn-epoxy coated steel, 2nd removal (144 days); ~500-ft, backside

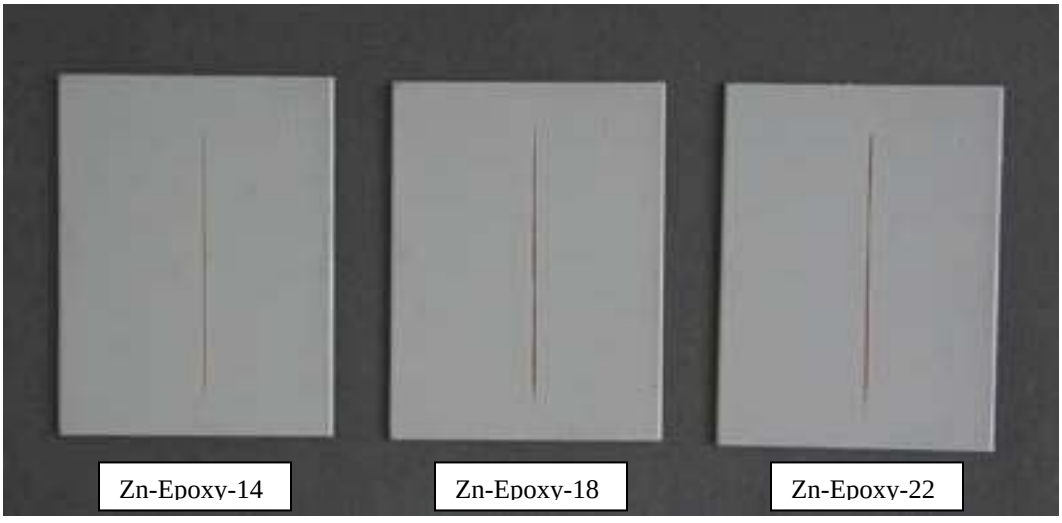


Figure 11c – Zn-epoxy coated steel, 2nd removal (143 days); ~2000-ft, front face

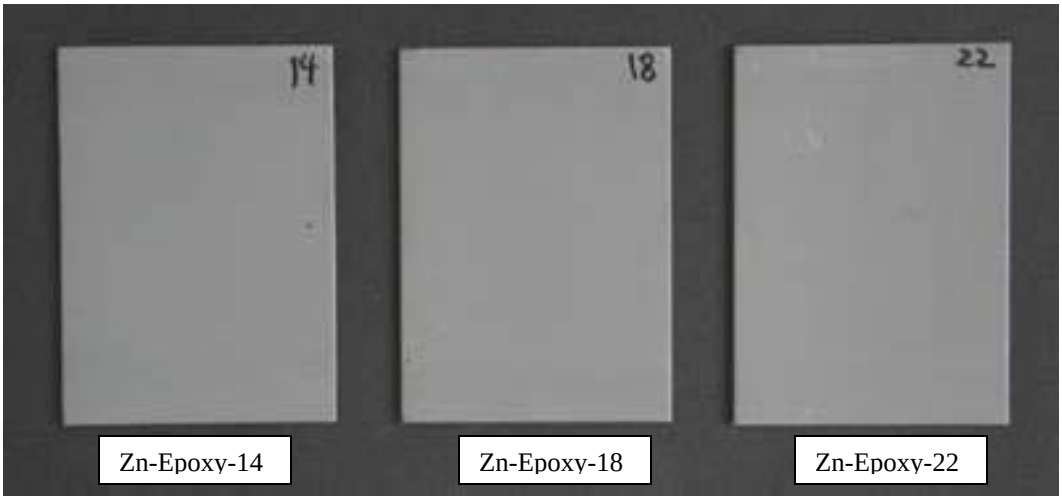


Figure 11d – Zn-epoxy coated steel, 2nd removal (143 days); ~2000-ft, backside

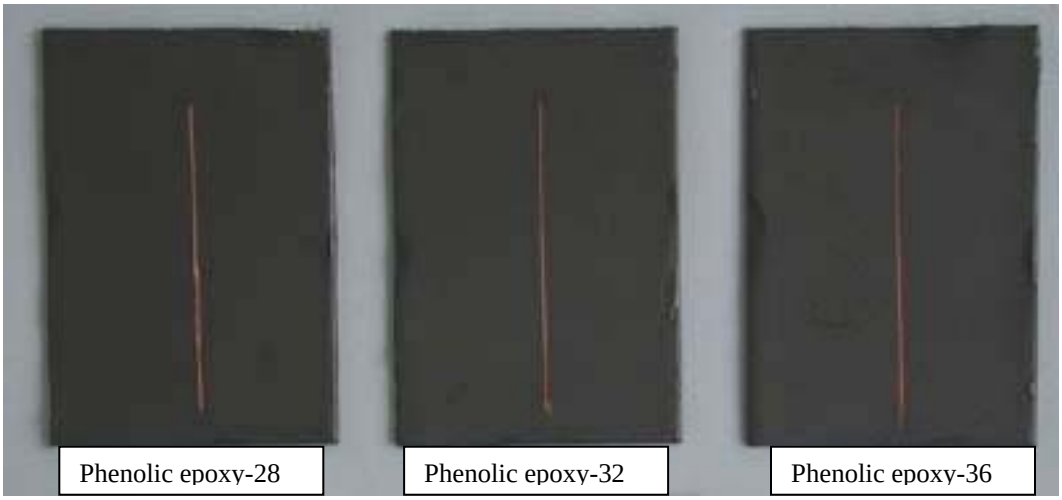


Figure 12a – Phenolic epoxy coated steel, 2nd removal (144 days); ~500-ft, front face

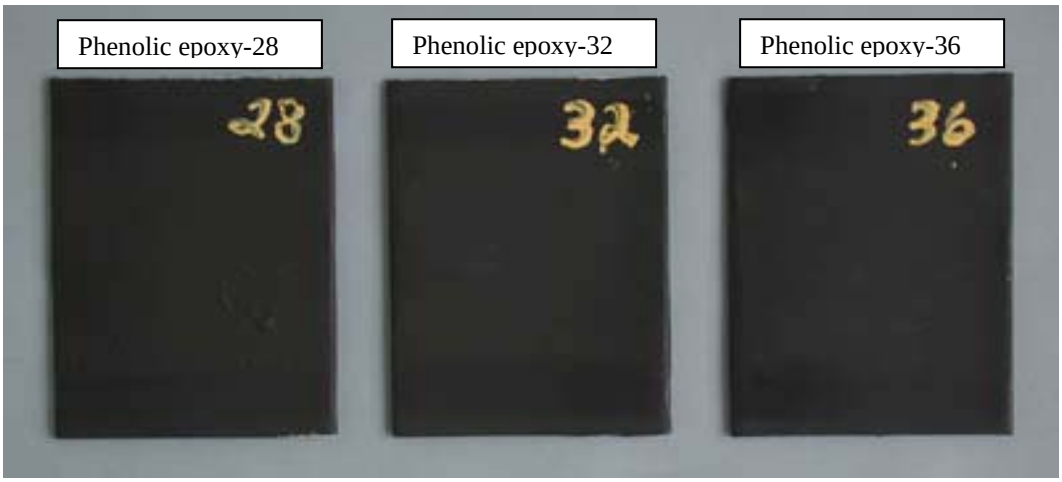


Figure 12b – Phenolic epoxy coated steel, 2nd removal (144 days); ~500-ft, backside; the "bubbles" in the coating on panel #28 are drips from the original application and not blisters due to coating deterioration

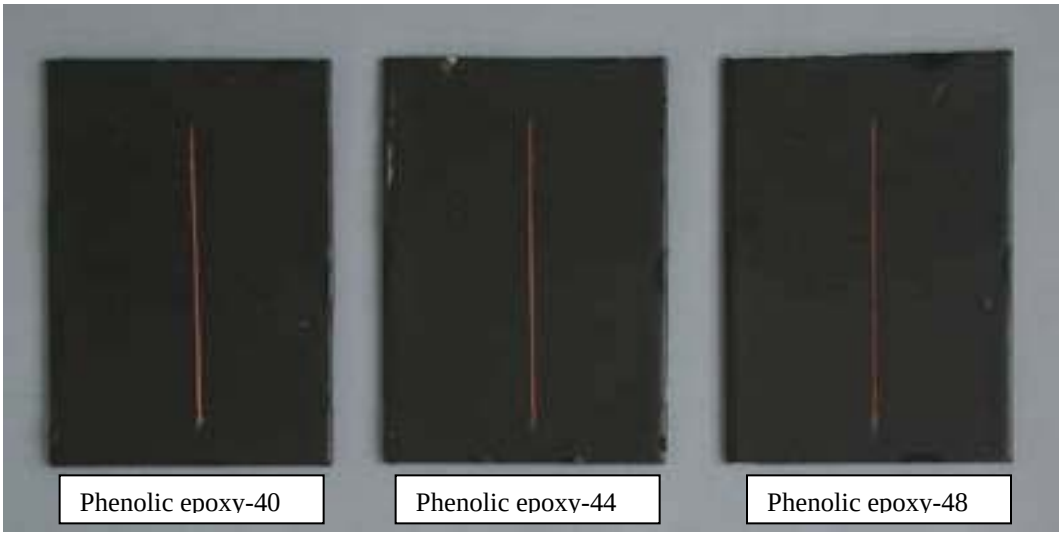


Figure 12c – Phenolic epoxy coated steel, 2nd removal (143 days); ~2000-ft, front face



Figure 12d – Phenolic epoxy coated steel, 2nd removal (143 days); ~2000-ft, backside

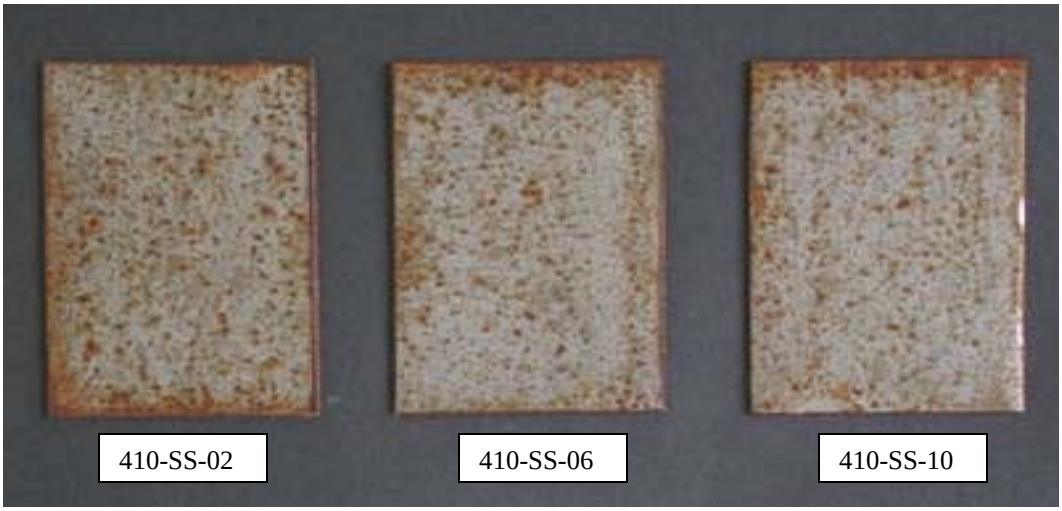


Figure 13a – 410 Stainless steel, 2nd removal (144 days); ~500-ft, front face

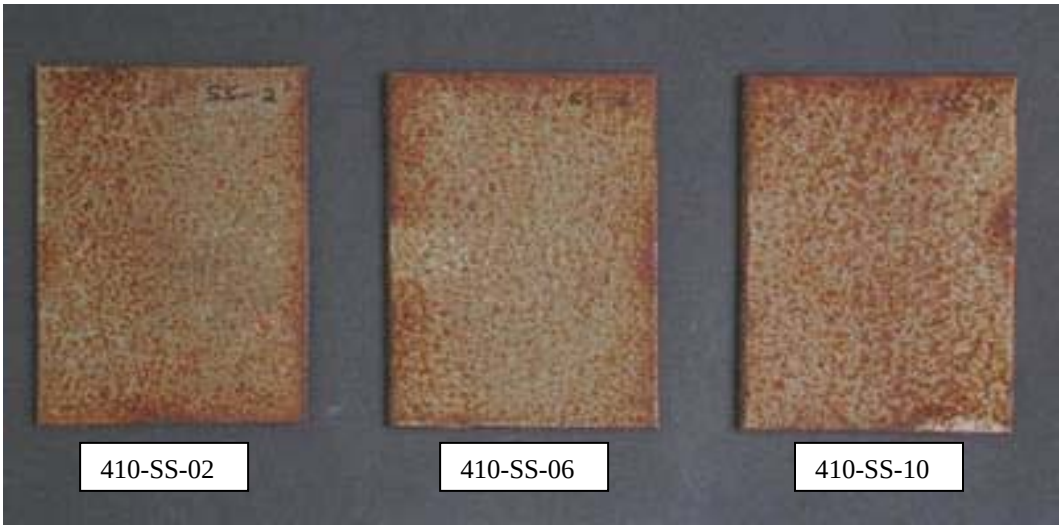


Figure 13b – 410 Stainless steel, 2nd removal (144 days); ~500-ft, backside

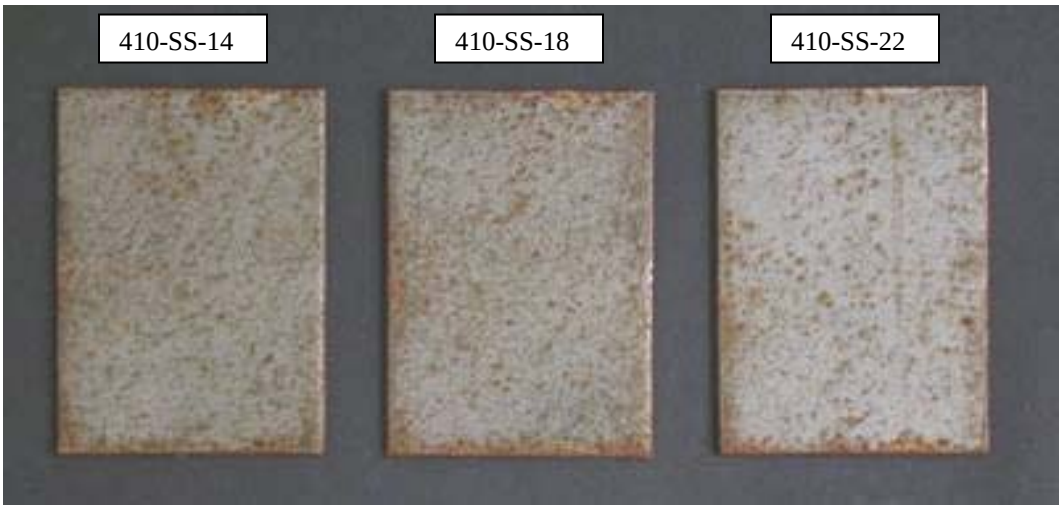


Figure 13c – 410 Stainless steel, 2nd removal (143 days); ~2000-ft, front face

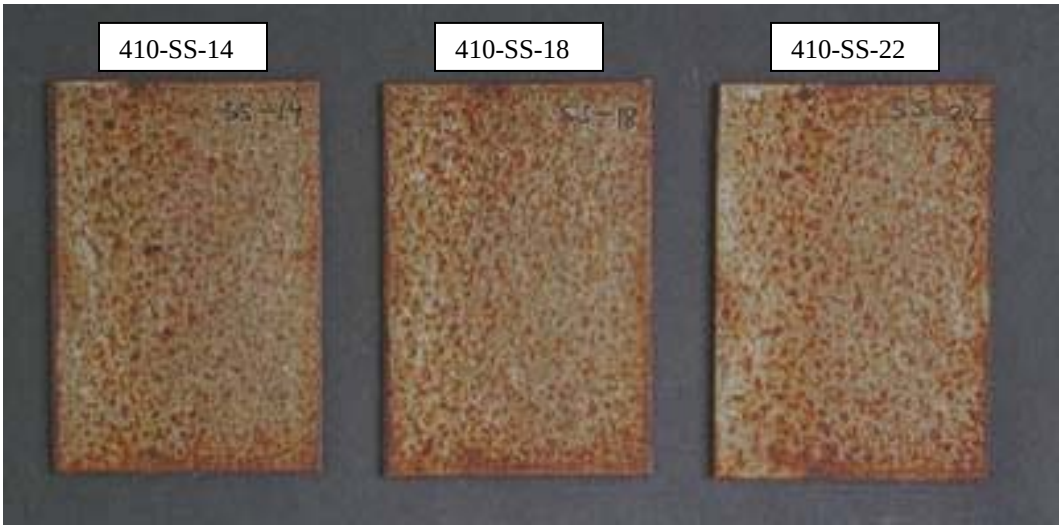


Figure 13d – 410 Stainless steel, 2nd removal (143 days); ~2000-ft, backside

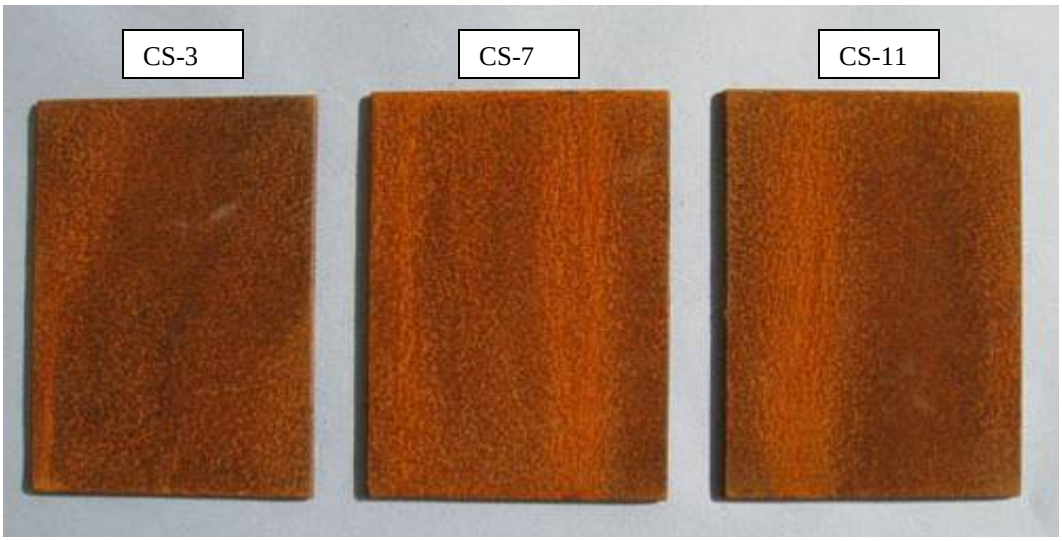


Figure 14a – Carbon steel, 3rd removal (213 days); ~500-ft, front face

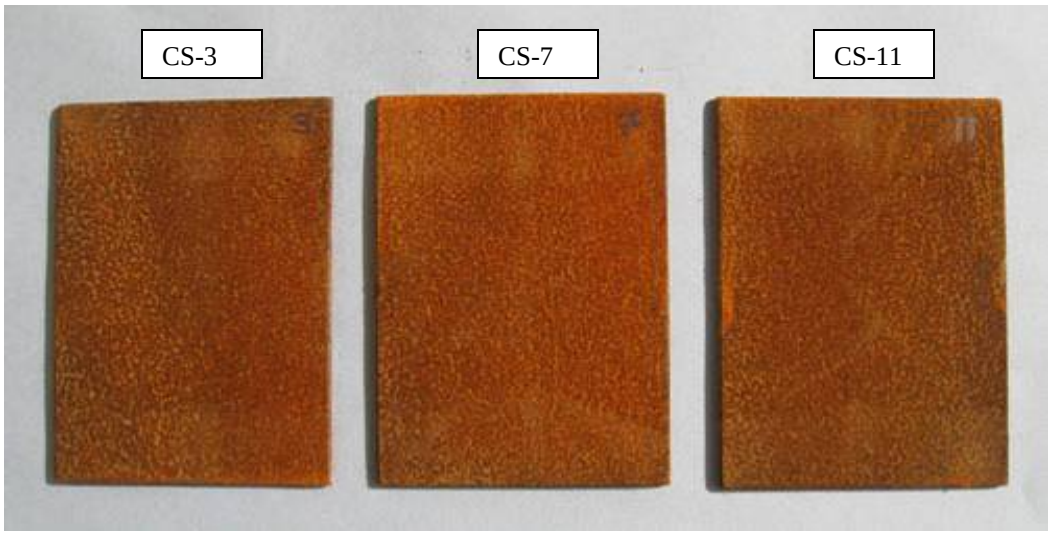


Figure 14b – Carbon steel, 3rd removal (213 days); ~500-ft, backside

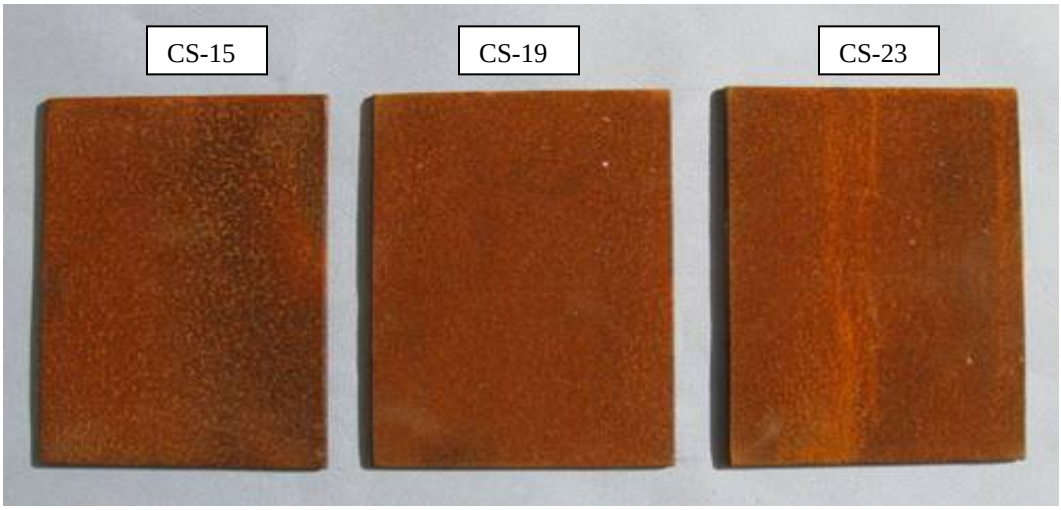


Figure 14c – Carbon steel, 3rd removal (212 days); ~2000-ft, front face

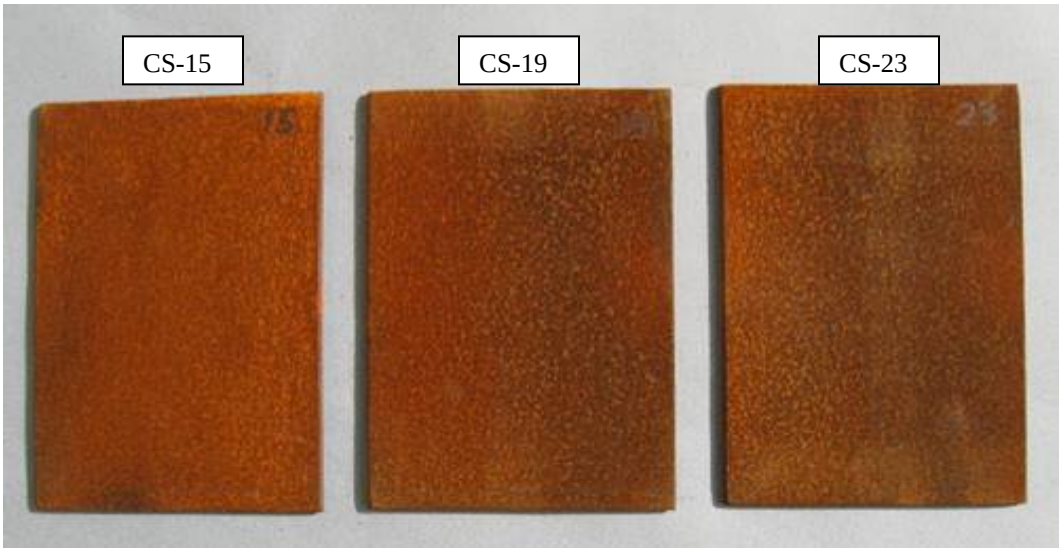


Figure 14b – Carbon steel, 3rd removal (212 days); ~2000-ft, backside

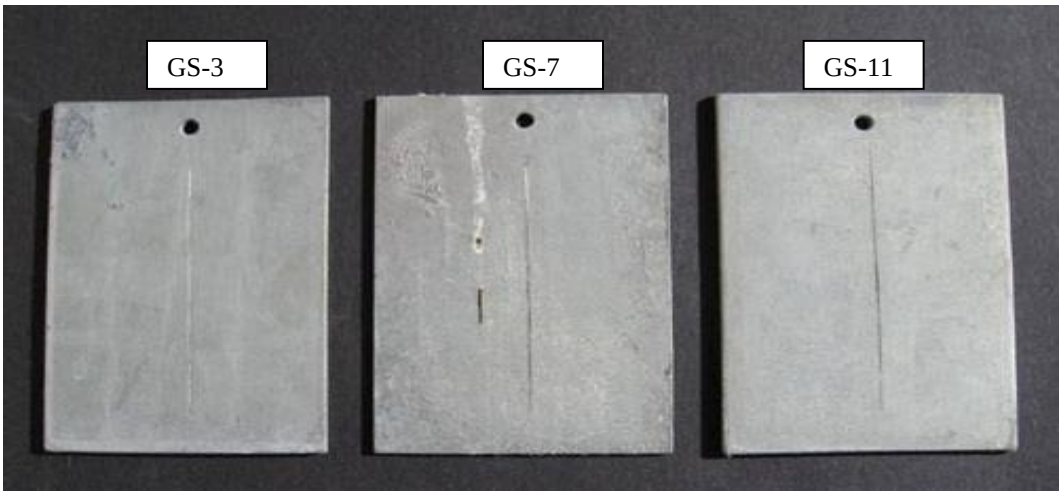


Figure 15a – Galvanized steel, 3rd removal (213 days); ~500-ft, front face

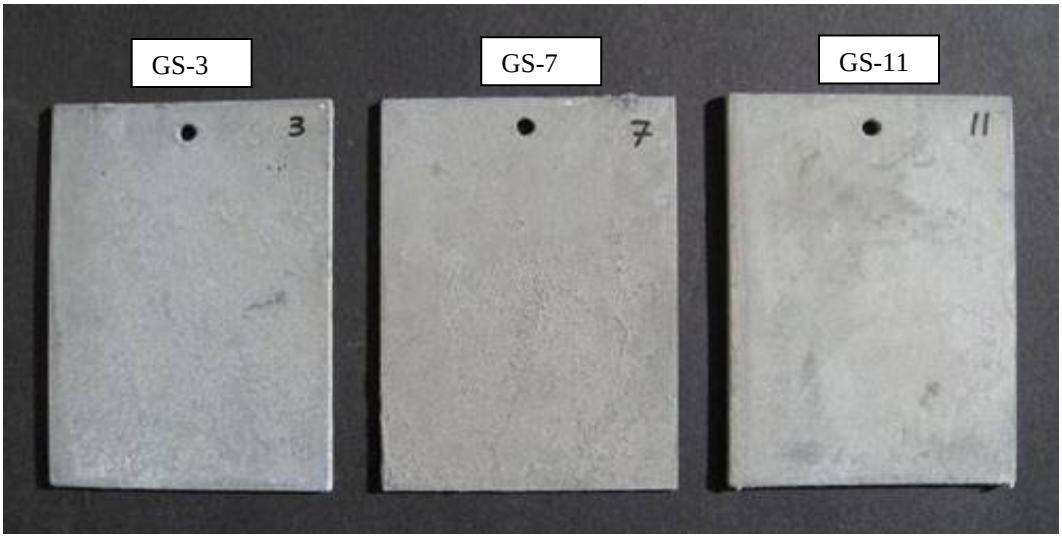


Figure 15b – Galvanized steel, 3rd removal (213 days); ~500-ft, backside

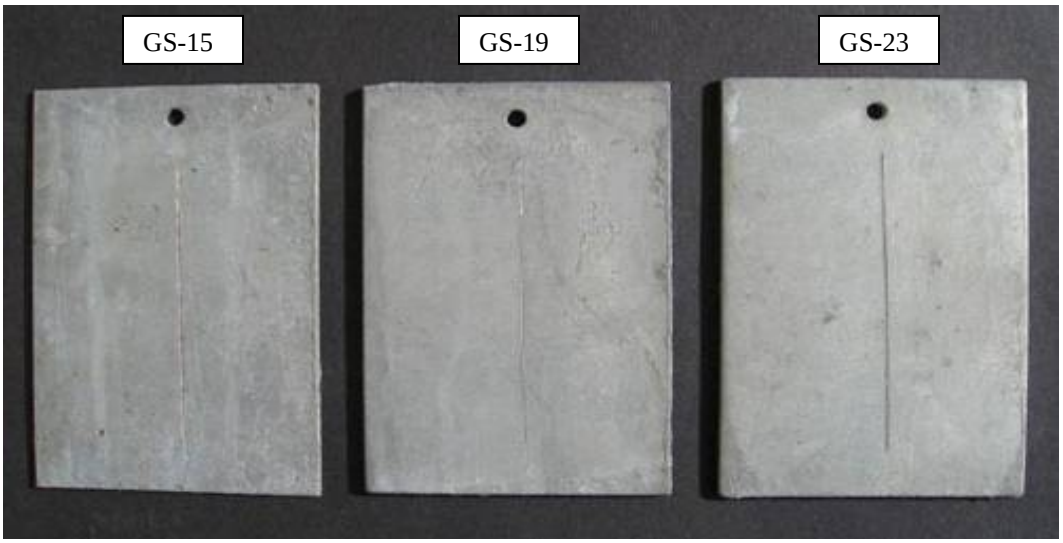


Figure 15c – Galvanized steel, 3rd removal (212 days); ~2000-ft, front face

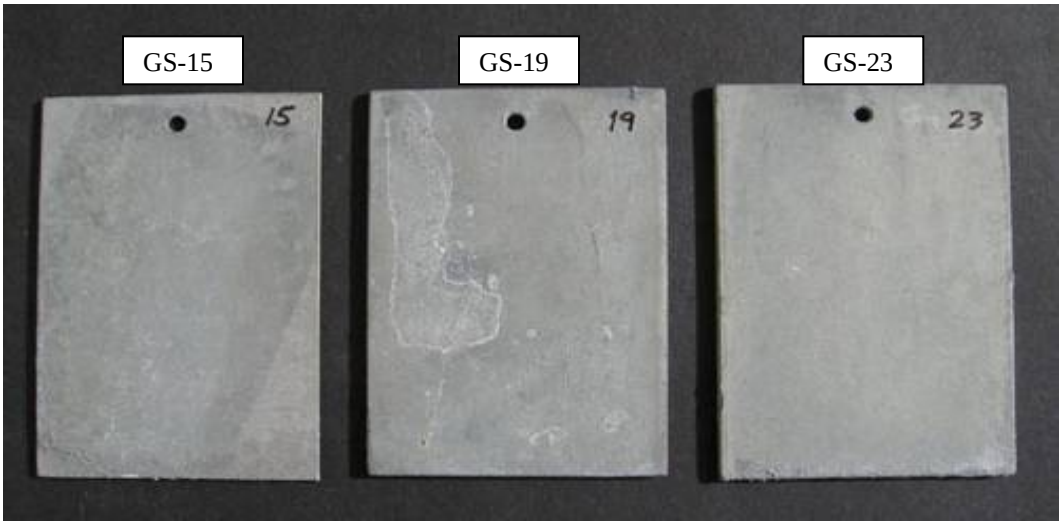


Figure 15d – Galvanized steel, 3rd removal (212 days); ~2000-ft, backside

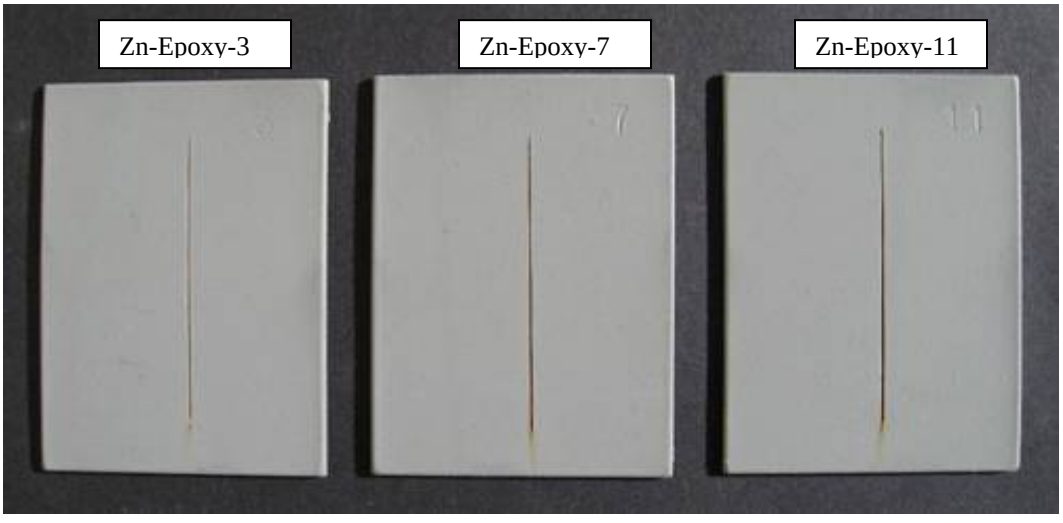


Figure 16a – Zn-epoxy coated steel, 3rd removal (213 days); ~500-ft, front face

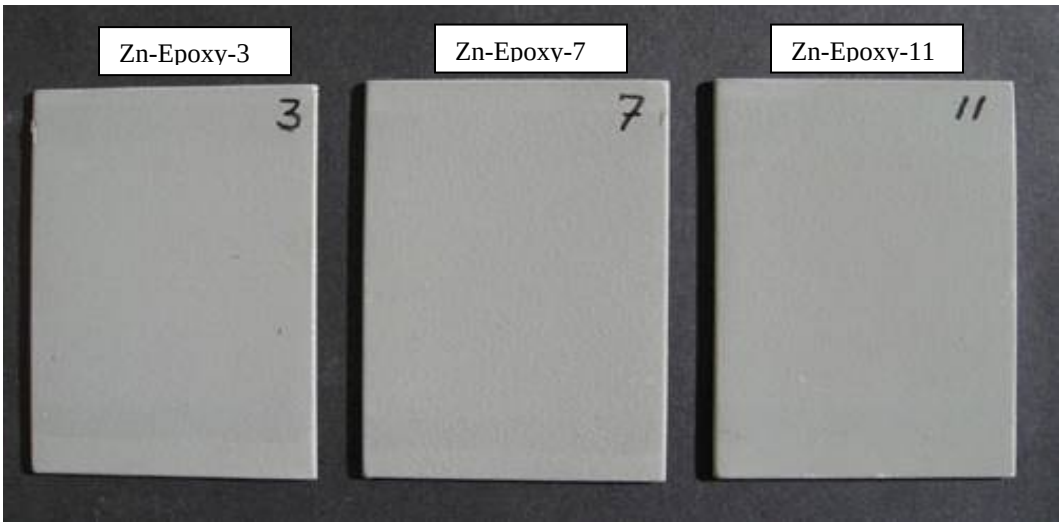


Figure 16b – Zn-epoxy coated steel, 3rd removal (213 days); ~500-ft, backside

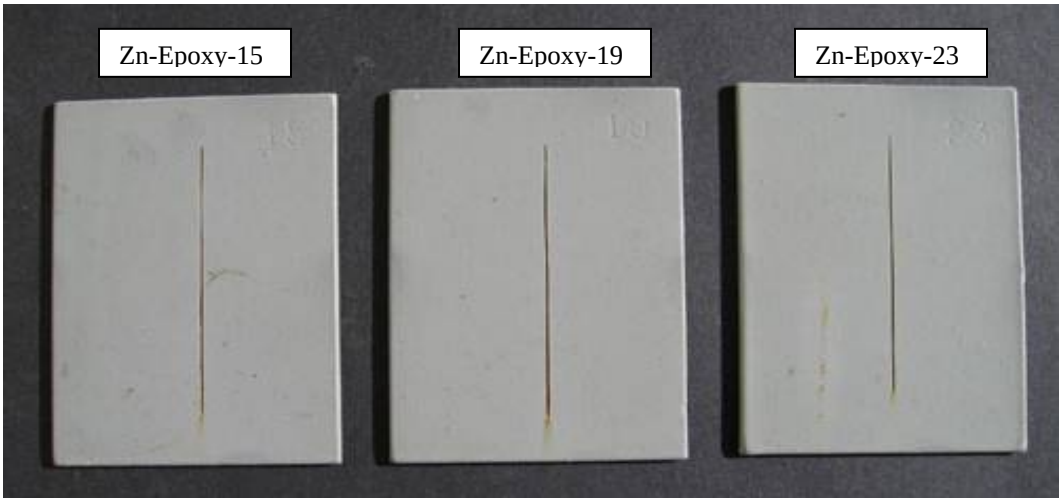


Figure 16c – Zn-epoxy coated steel, 3rd removal (212 days); ~2000-ft, front

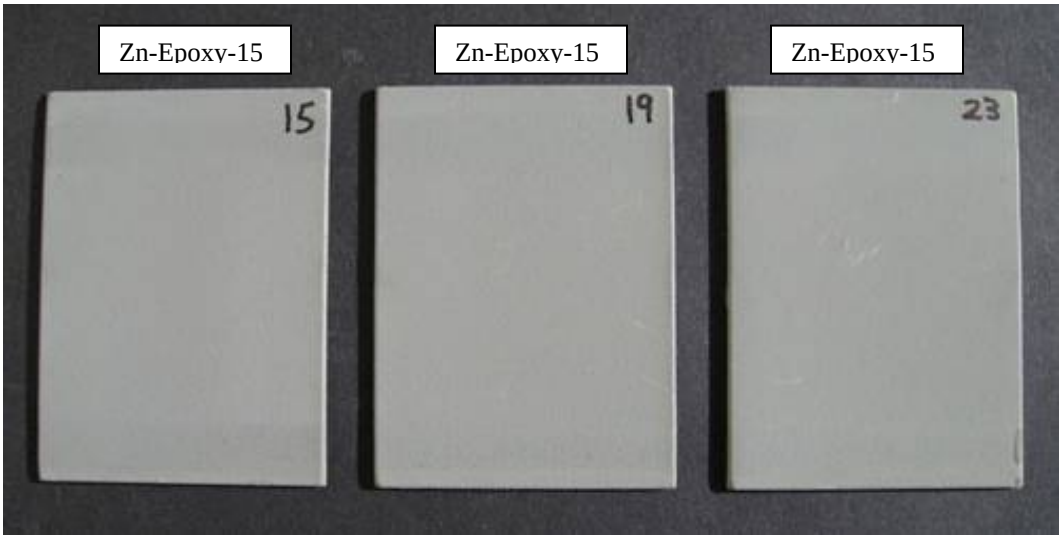


Figure 16d – Zn-epoxy coated steel, 3rd removal (212 days); ~2000-ft, backside

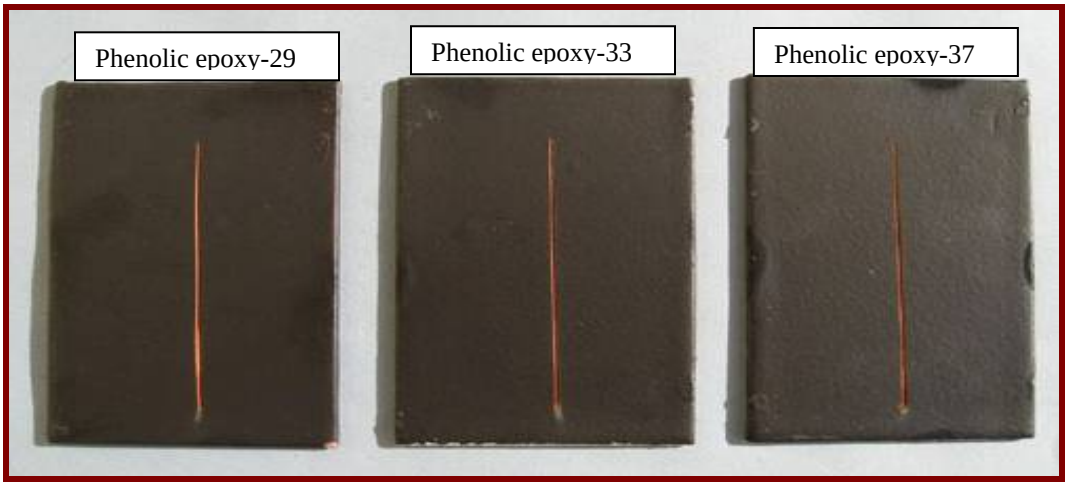


Figure 17a – Phenolic epoxy coated steel, 3rd removal (213 days); ~500-ft, front face

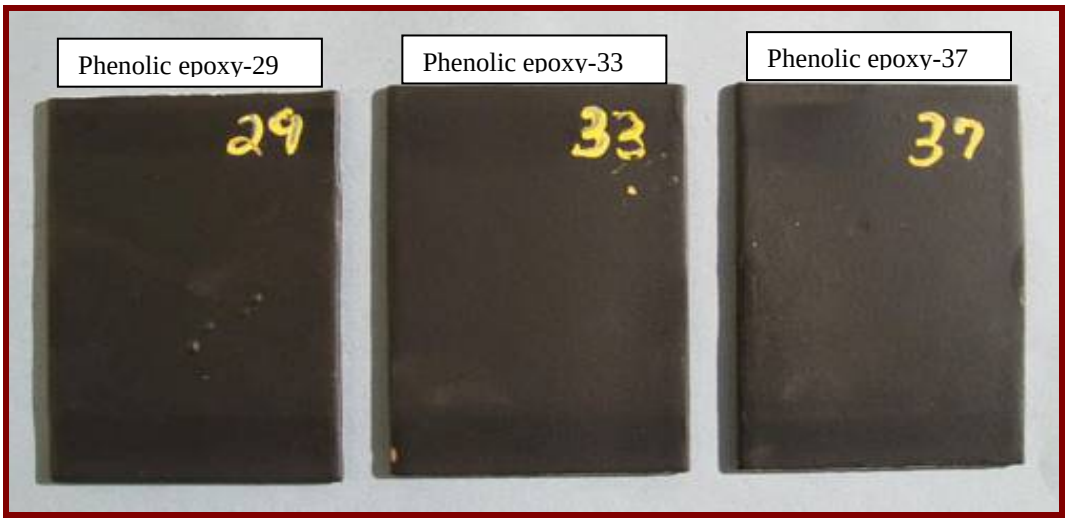


Figure 17b – Phenolic epoxy coated steel, 3rd removal (213 days); ~500-ft, backside. The "bubbles" in the coating on panel #29 are drips from the original application and not blisters due to coating deterioration.

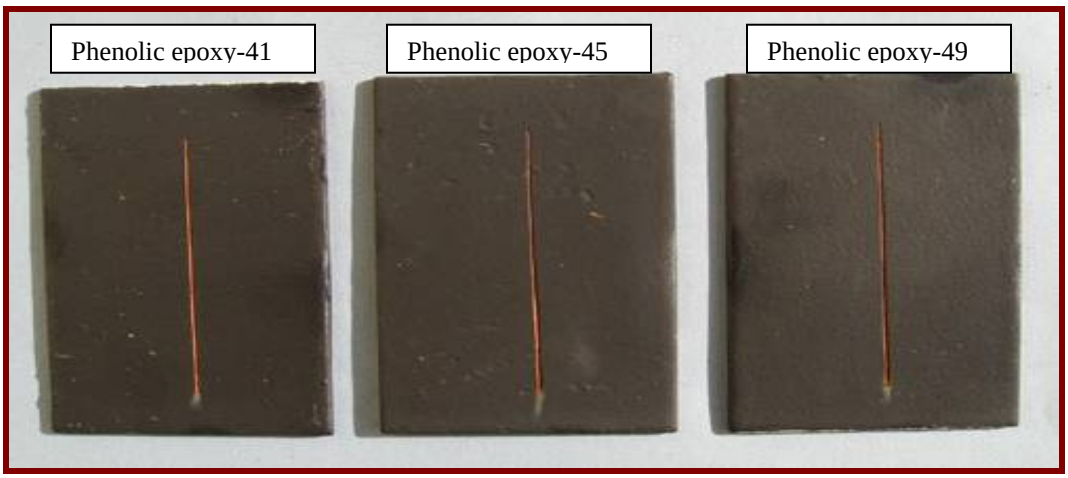


Figure 17c – Phenolic epoxy coated steel, 3rd removal (212 days); ~2000-ft, front face; indentations on the coated panels were present before exposure

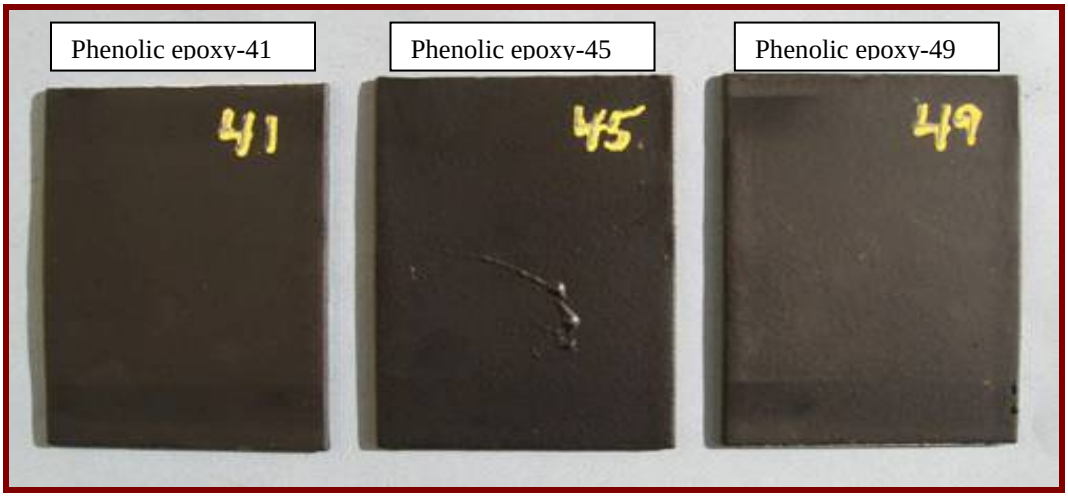


Figure 17d – Phenolic epoxy coated steel, 3rd removal (212 days); ~2000-ft, backside.
The "bubbles" in the coating on panel #45 are drips from the original application and not blisters due to coating deterioration

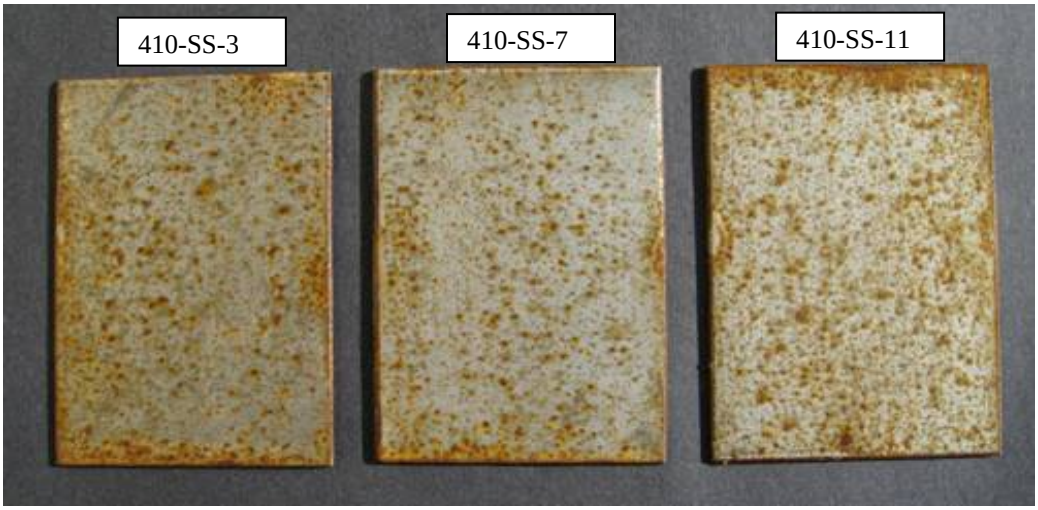


Figure 18a – 410 Stainless steel, 3rd removal (213 days); ~500-ft, front face

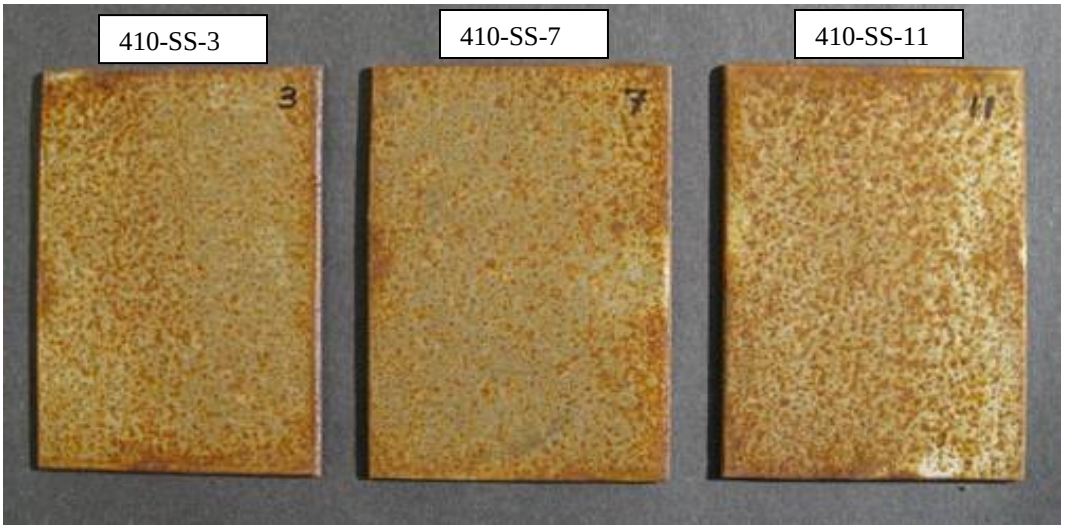


Figure 18b – 410 Stainless steel, 3rd removal (213 days); ~500-ft, backside

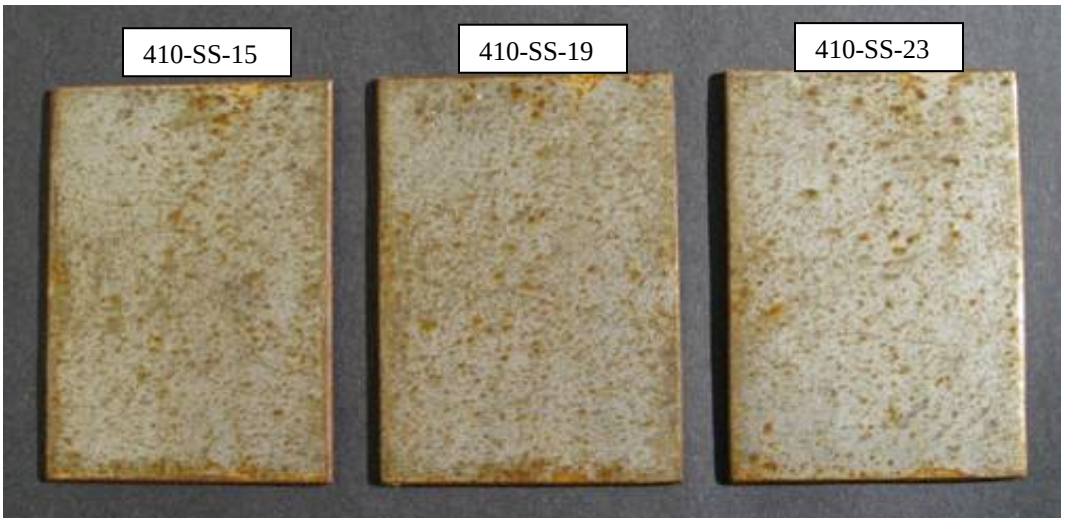


Figure 18c – 410 Stainless steel, 3rd removal (212 days); ~2000-ft, front face

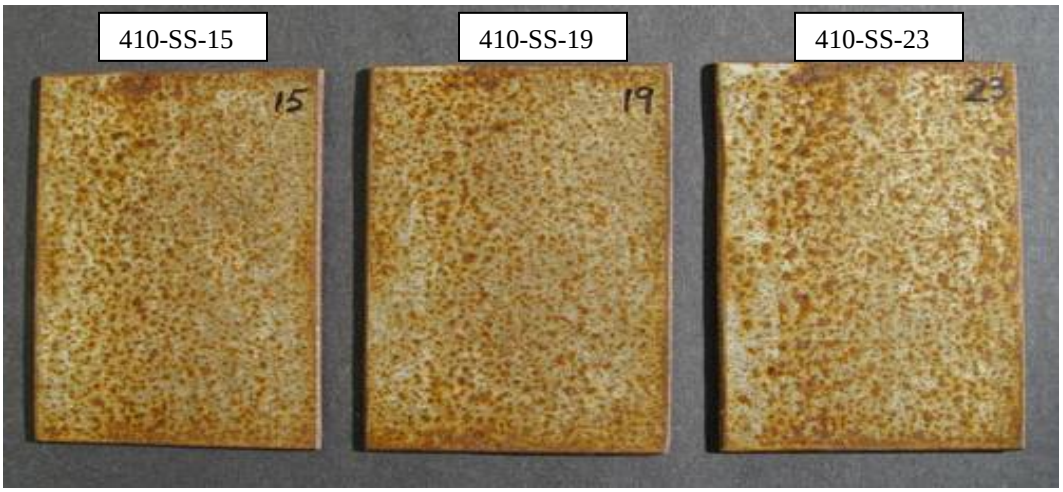


Figure 18d – 410 Stainless steel, 3rd removal (212 days); ~2000-ft, backside

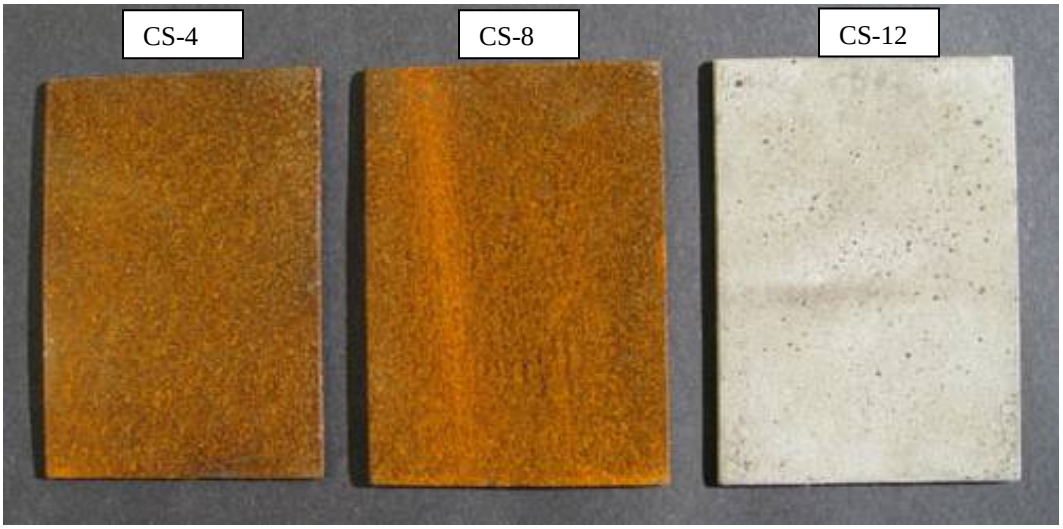


Figure 19a – Carbon steel, 4th removal (247 days); ~500-ft, front face
(Panel CS-12 – After cleaning)

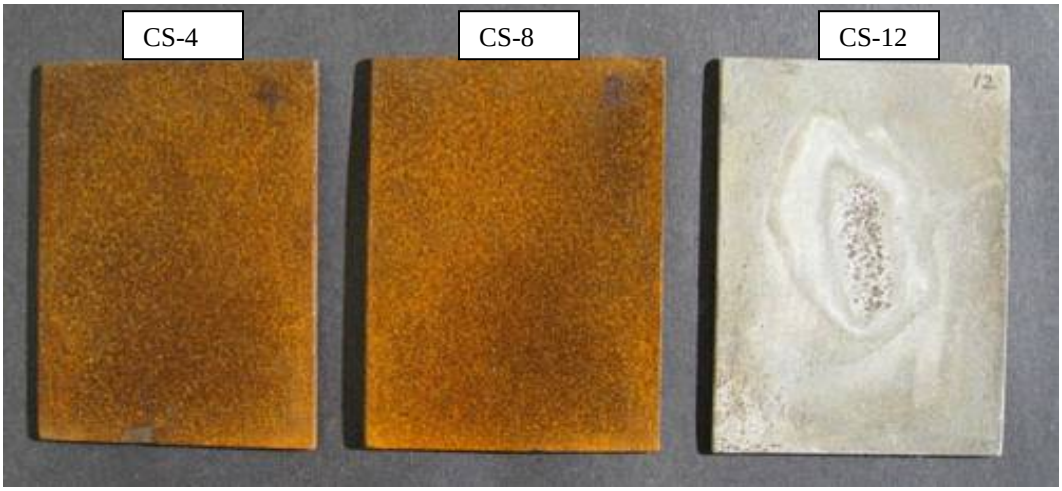


Figure 19b - Carbon steel, 4th removal (247 days); ~500-ft, backside
(Panel CS-12 – After cleaning)

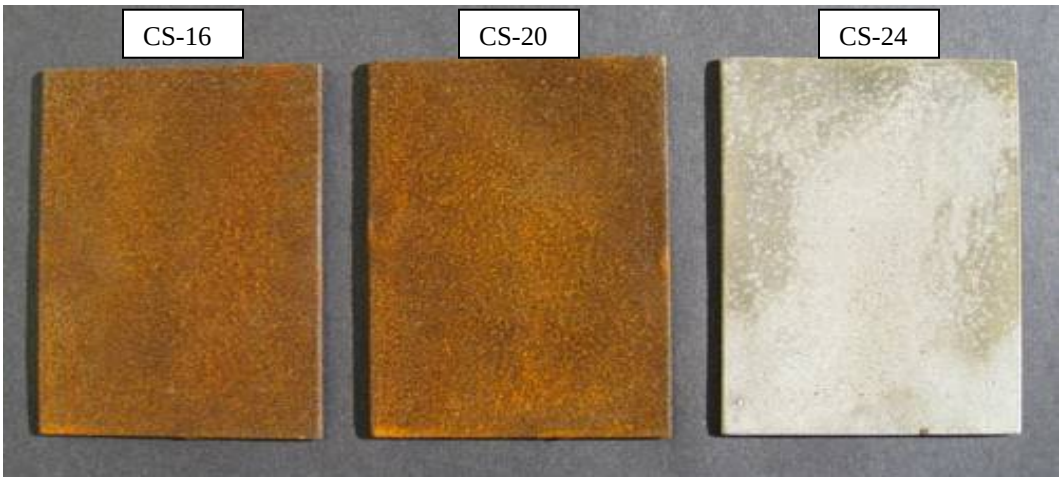


Figure 19c - Carbon steel, 4th removal (246 days); ~2000-ft, front face
(Panel CS-24 – After cleaning)

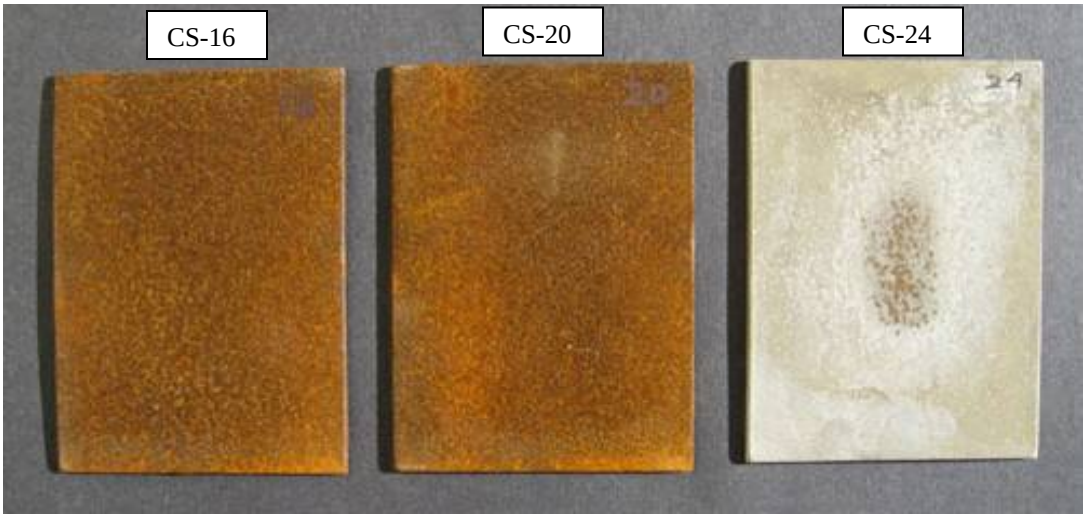


Figure 19d - Carbon steel, 4th removal (246 days); ~2000-ft, backside
(Panel CS-24 – After cleaning)

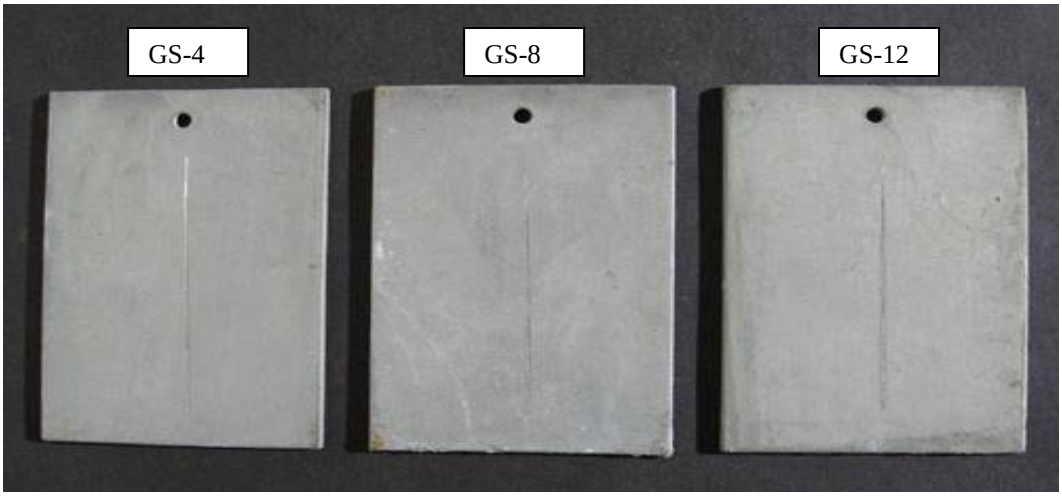


Figure 20a - Galvanized steel, 4th removal (247 days); ~500-ft, front face

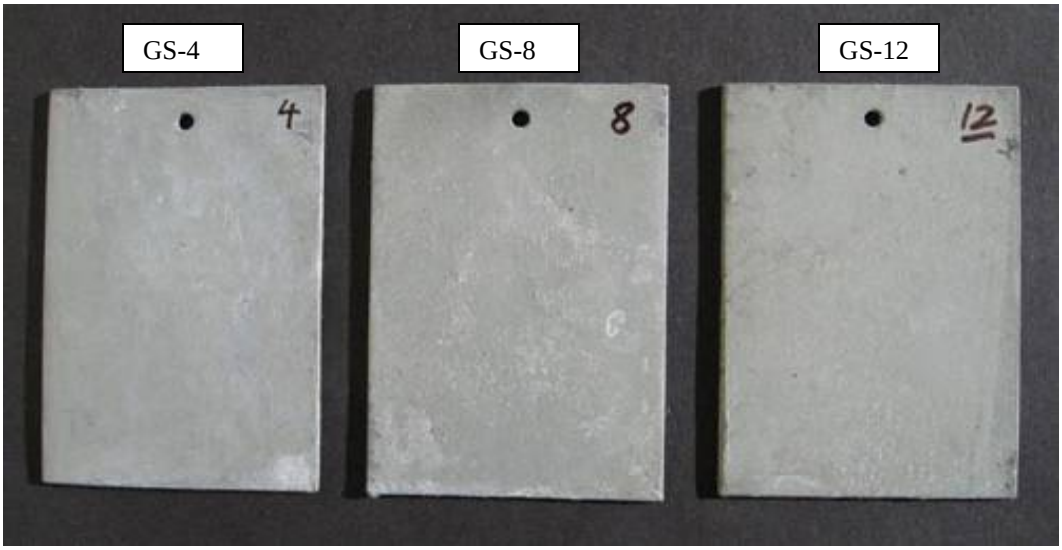


Figure 20b – Galvanized steel, 4th removal (247 days); ~500-ft, backside

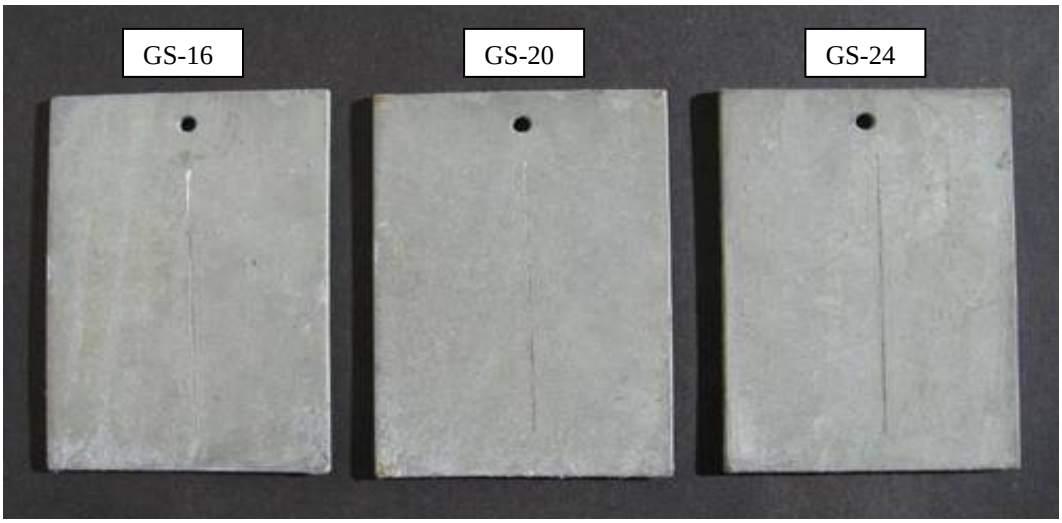


Figure 20c – Galvanized steel, 4th removal (246 days); ~2000-ft, front face

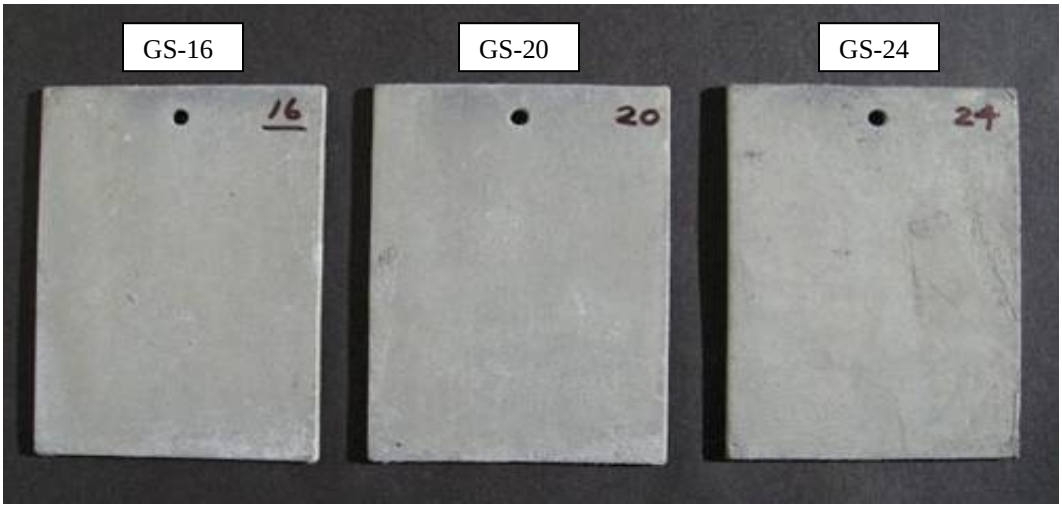


Figure 20c – Galvanized steel, 4th removal (246 days); ~2000-ft, backside

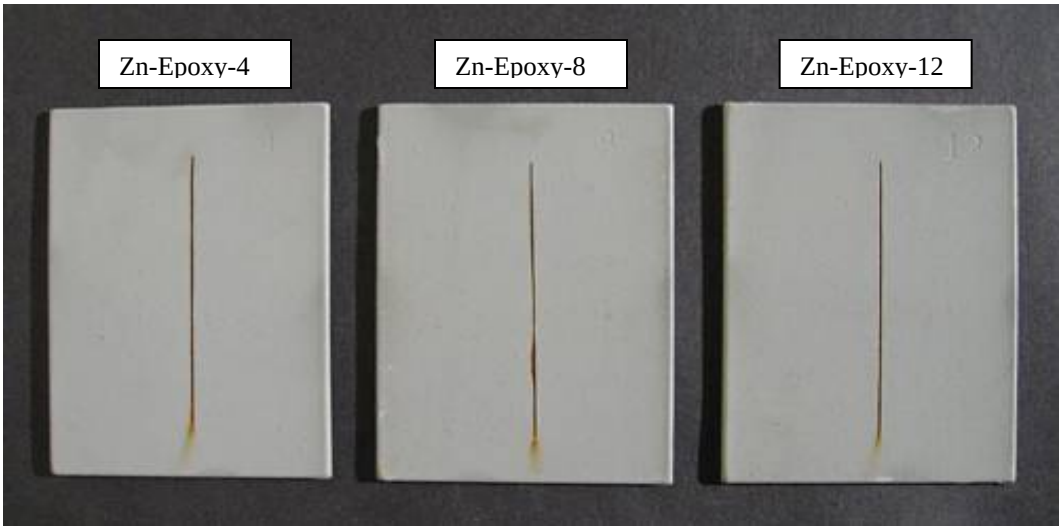


Figure 21a – Zn-epoxy coated steel, 4th removal (247 days); ~500-ft, front face

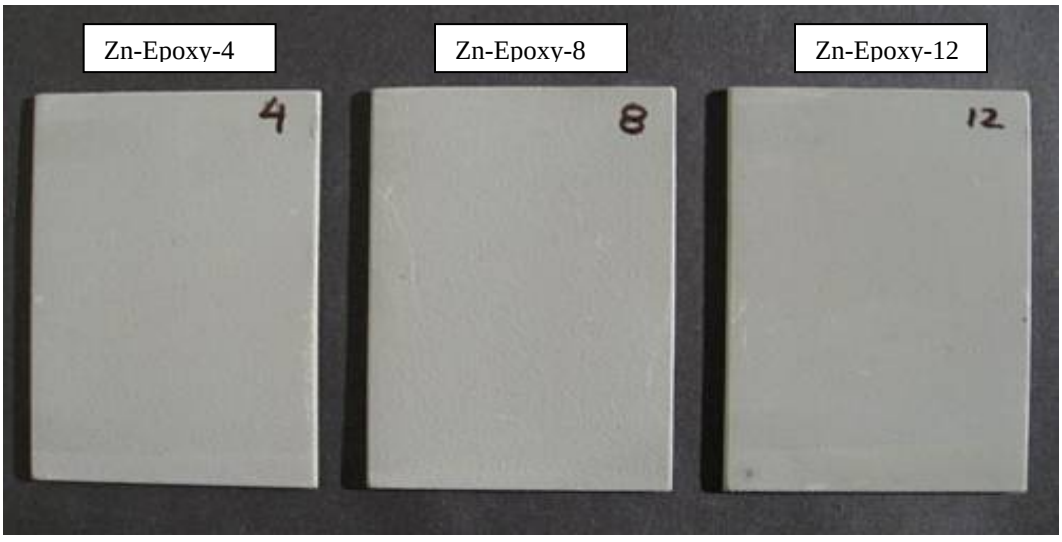


Figure 21b – Zn-epoxy coated steel, 4th removal (247 days); ~500-ft, backside

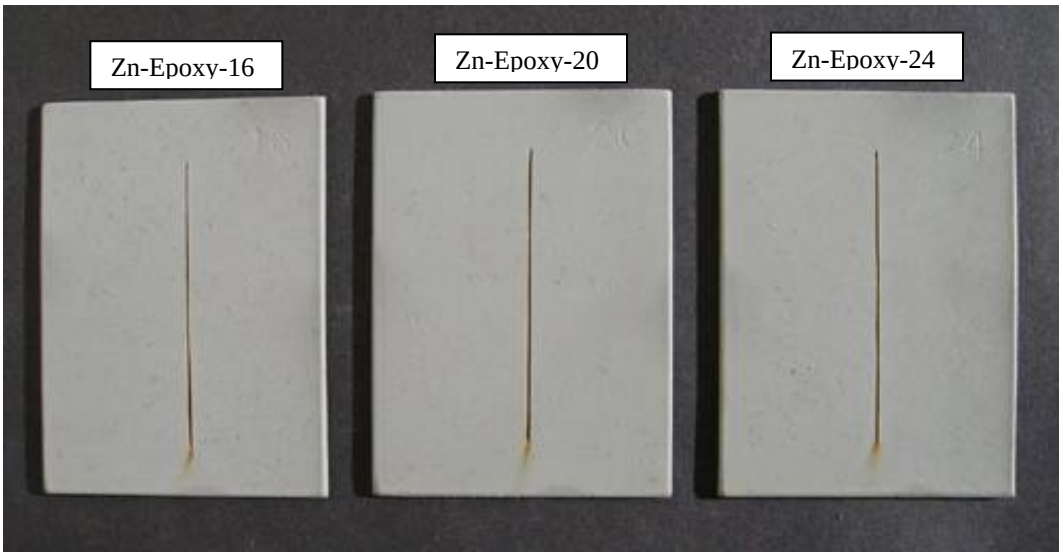


Figure 21c – Zn-epoxy coated steel, 4th removal (246 days); ~2000-ft, front face

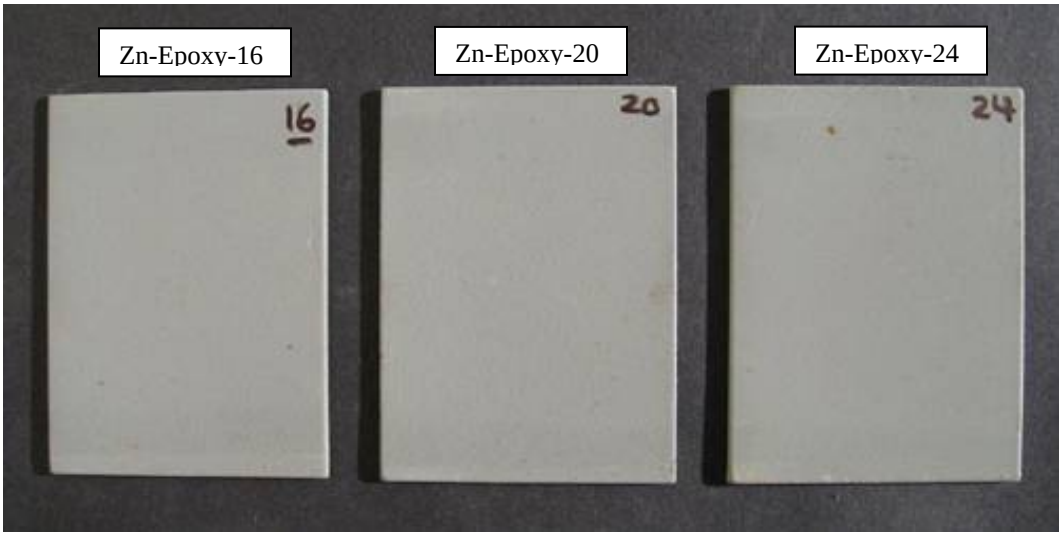


Figure 21d – Zn-epoxy coated steel, 4th removal (246 days); ~2000-ft, backside

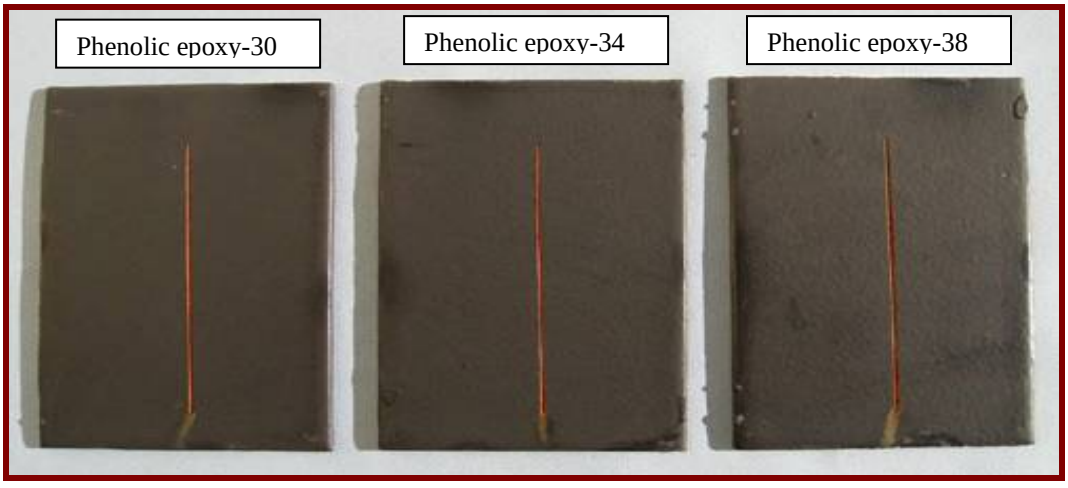


Figure 22a – Phenolic epoxy coated steel, 4th removal (247 days); ~500-ft, front face

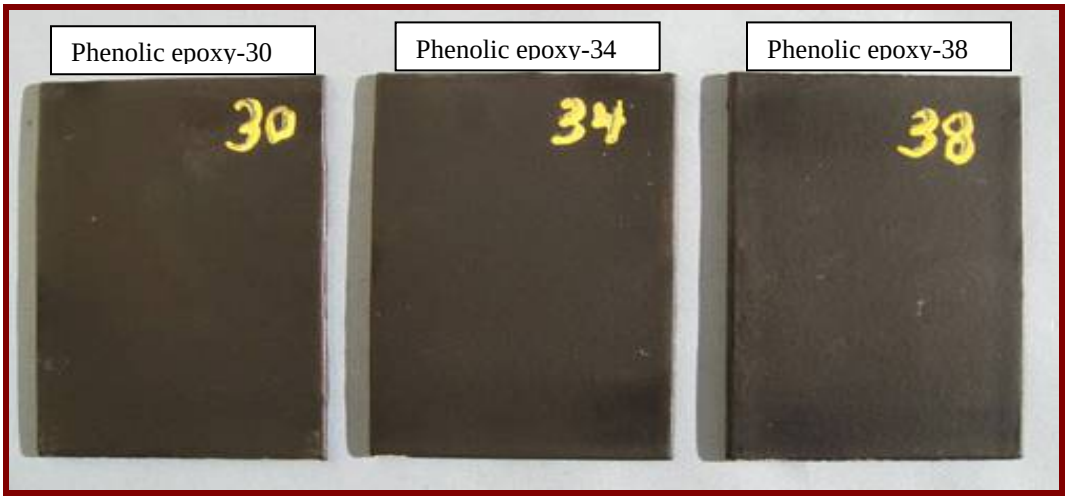


Figure 22b – Phenolic epoxy coated steel, 4th removal (247 days); ~500-ft, backside

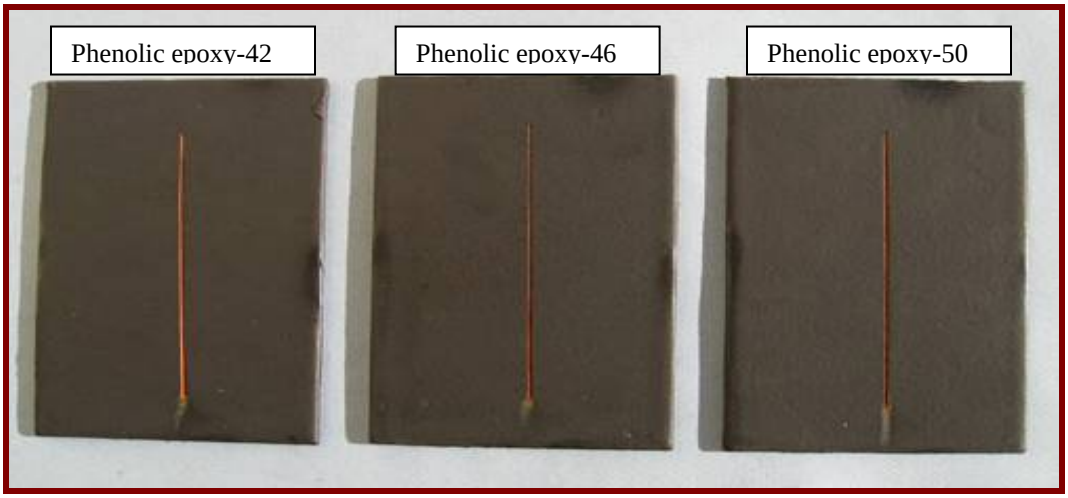


Figure 22c – Phenolic-epoxy coated steel, 4th removal (246 days); ~2000-ft, front face

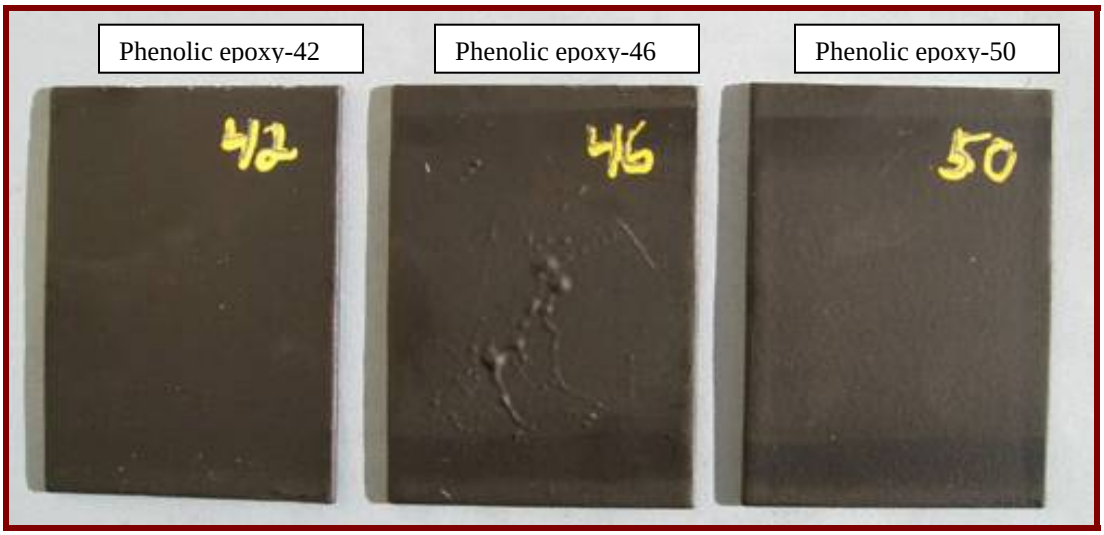


Figure 22d – Phenolic-epoxy coated steel, 4th removal (246 days); ~2000-ft, backside.

The "bubbles" in the coating on panel #46 are drips from the original application and not blisters due to coating deterioration.

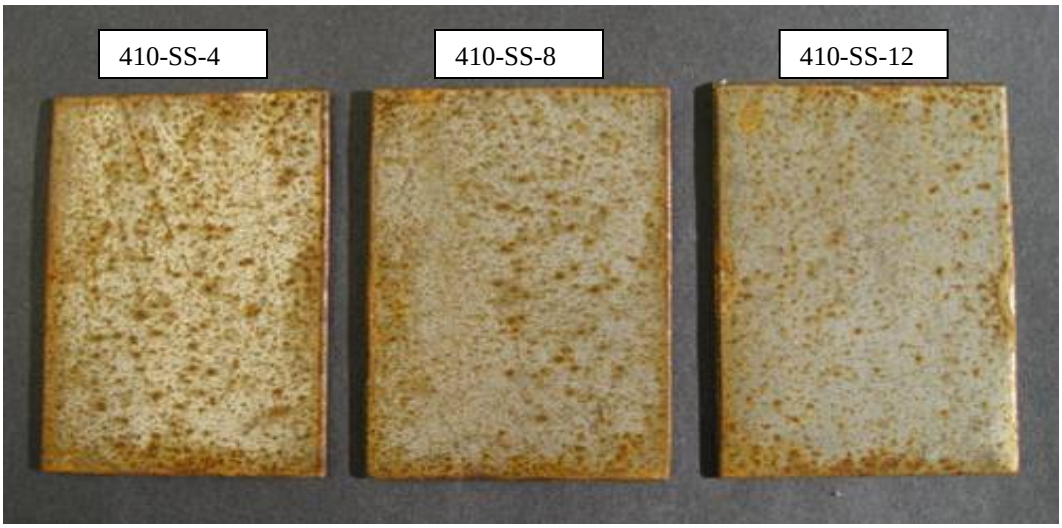


Figure 23a – 410 Stainless steel, 4th removal (247 days); ~500-ft, front face

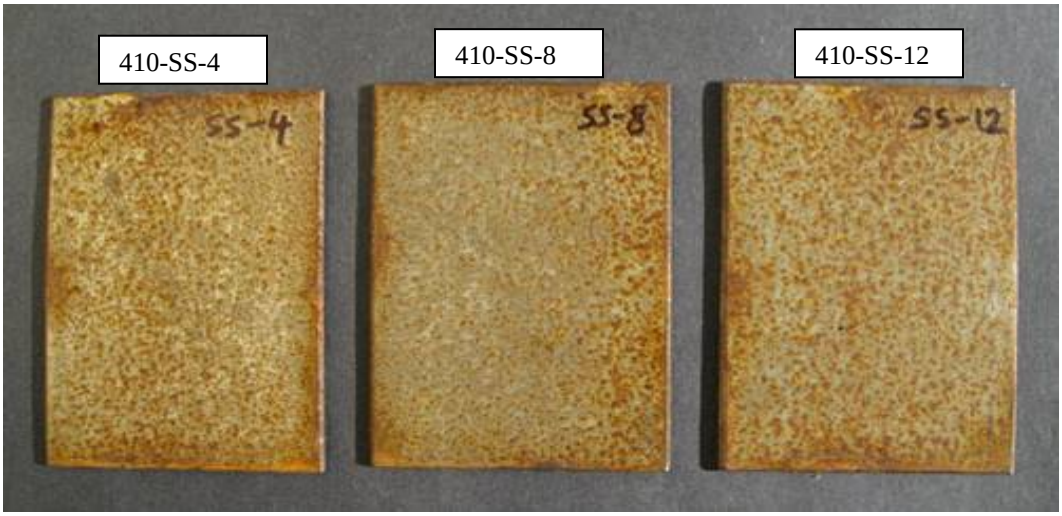


Figure 23b – 410 Stainless steel, 4th removal (247 days); ~500-ft, backside

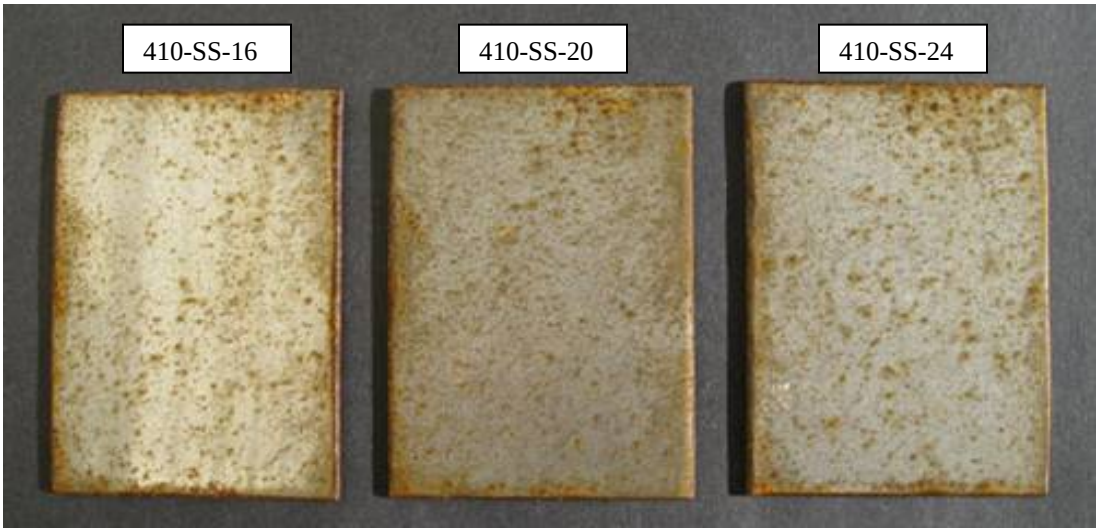


Figure 23c – 410 Stainless steel, 4th removal (246 days); ~2000-ft, front face

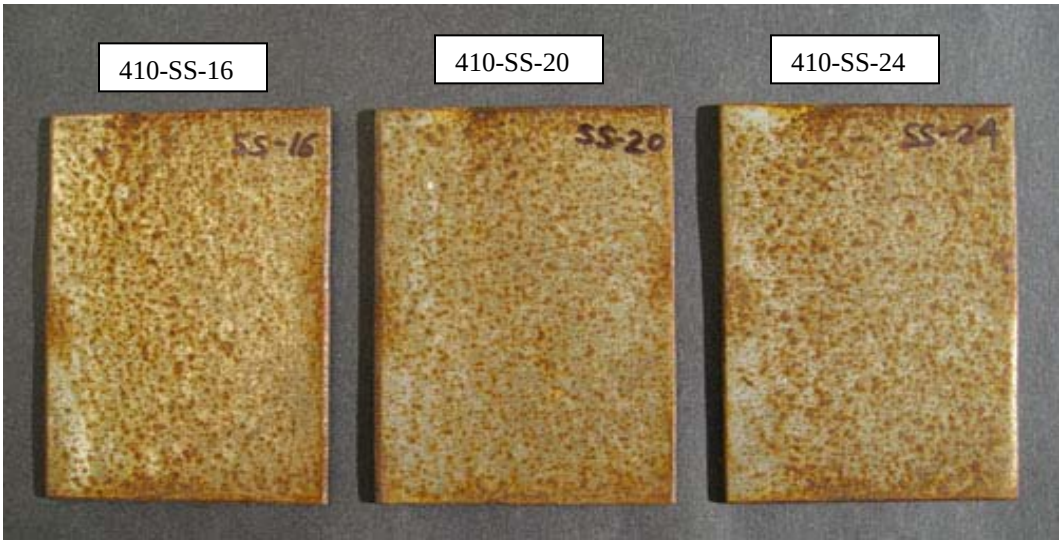


Figure 23d – 410 Stainless steel, 4th removal (246 days); ~2000-ft, backside

Appendix G: LPR System Components and Site Installation Details

Components and Test Materials for the Corrosion Sensor Monitoring System Test at Torii

Enclosures for 1) sensor electronics and 2) junction box to access the system:

Waterproof electronics enclosure
Waterproof RS-232 jacks
Waterproof RS-232 connectors
IP-67 waterproof connectors
Custom gum com carrier board
AA battery holders
Custom front panel
Waterproof junction box
50' outdoor RS-232 cable
3/16" Masonry drill bit
¼" Masonry Anchor bolts

Sensors assembly parts in addition to the LPR corrosion sensors such as:

IP-67 waterproof plugs
Spool of 500' 22/2 shielded cable

Supplies paint compatibility quality control experiment to be performed before shipping:

Water based Tile-Clad® Epoxy Primer
Water based Tile-Clad® Epoxy Finish
Two 2 gallon paint buckets
5 minute 2 part epoxy
2'X2' 1010 steel sheet metal
Two Rubbermaid plastic tubs with lids
Wet coating thickness gauge

Supplies for Torii Station Okinawa Japan installation supplies:

Water based Tile-Clad® Epoxy Primer
Water based Tile-Clad® Epoxy Finish
Nylon/Polyester paint brushes
5 minute 2 part epoxy
Cable tie downs
Zip ties
Tape
Two 2 gallon paint buckets
Paint mixer
Wet coating thickness gauge

Building Where Monitoring System is Installed and Schematics



Figure 1: Facility identification number on building where tests occurred



Figure 2: View of building T-125

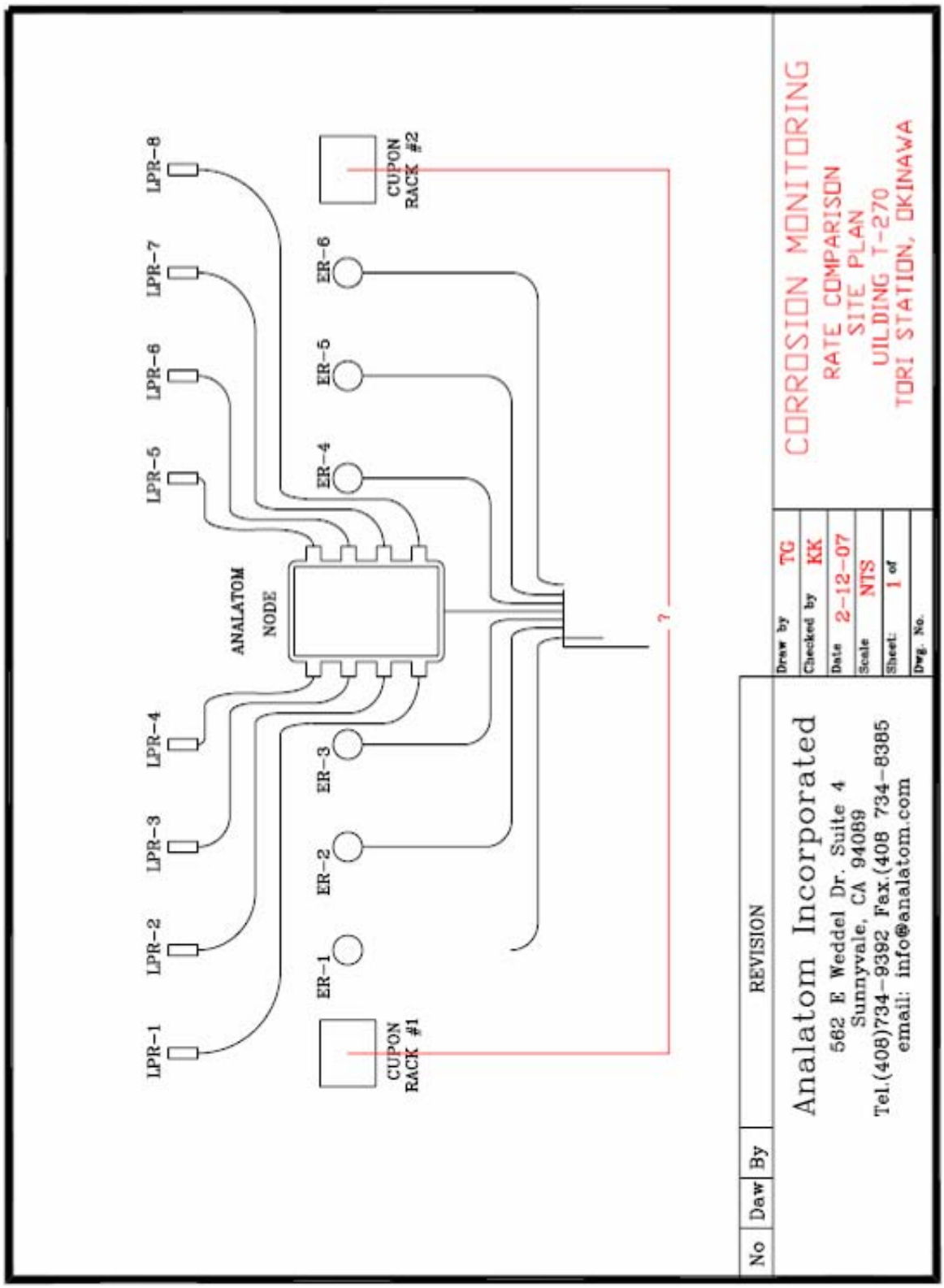


Figure 3. LPR corrosion sensor layout for roof installation.

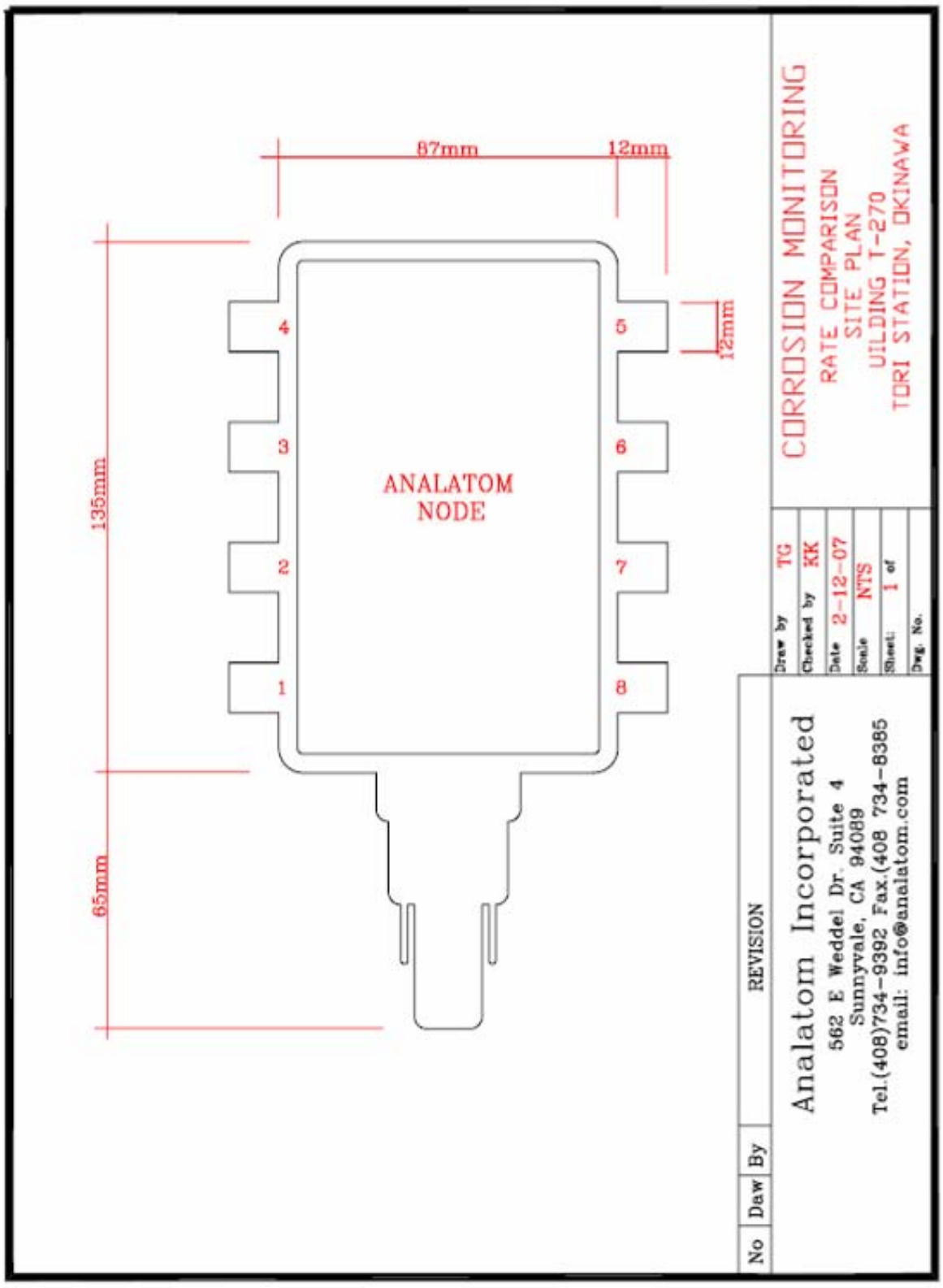


Figure 4: Analatom LPR corrosion sensor system node schematic.

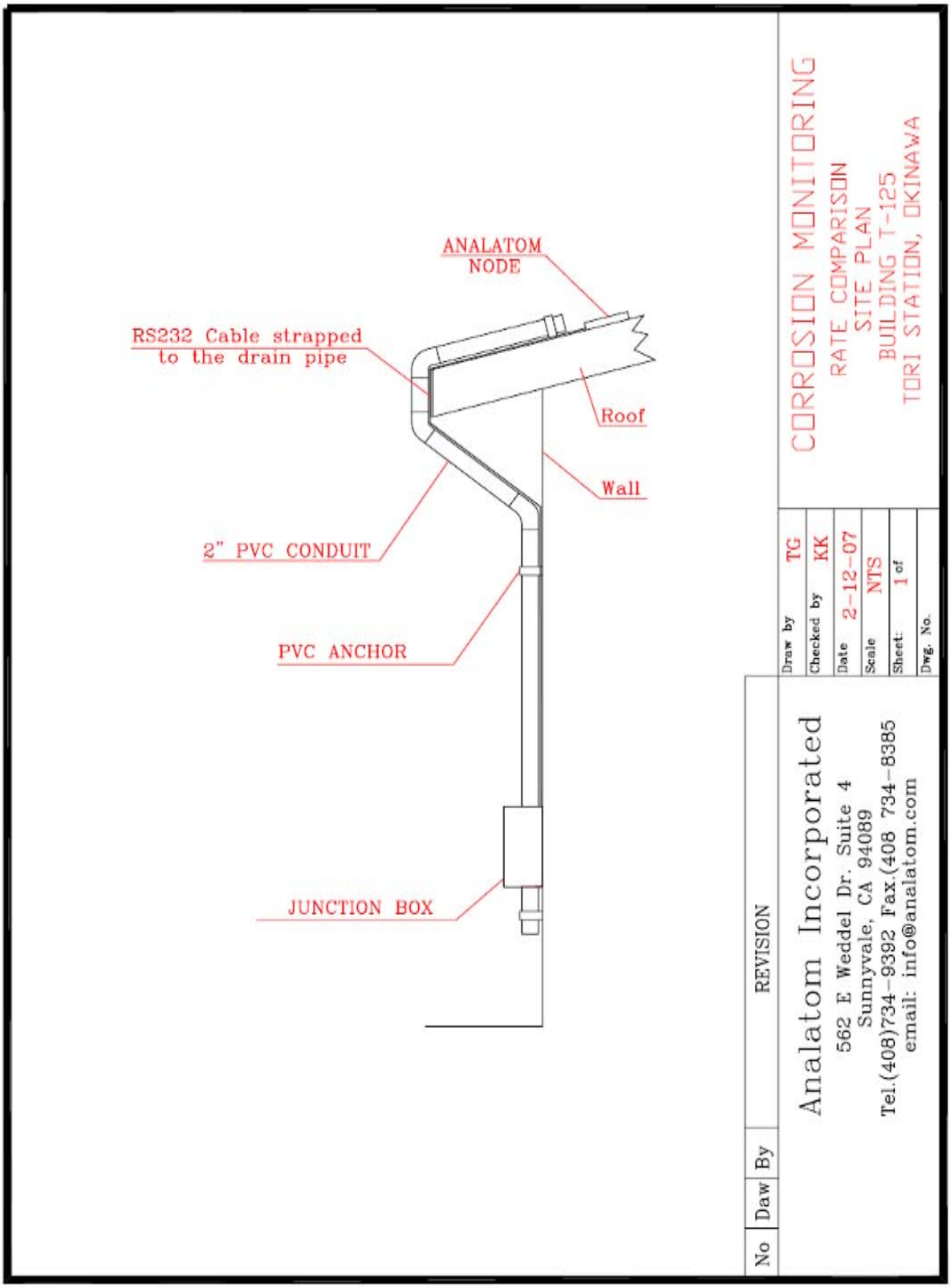


Figure 5: Cross Section of the Side Wall to Strap the RS232 Data Cable to the Drain Pipe

Description of Installation of Corrosion Sensor System

A photo of the roof before installation of the sensors is shown in Figure 6.



Figure 6: Roof of building where LPR corrosion sensors were installed.

The first step involved determining the cable lengths needed to connect the Analatom corrosion sensors to the data acquisition box. It was determined that the sensors should be placed in close proximity to six ER probes and two corrosion coupon racks that had previously been installed by Corrosion Control, Inc.

The sensor leads were then cut to the correct length, and the sensors were fixed in place on the roof using an epoxy. The sensor cables were securely fastened to the roof.

Tape was then applied around the sensors in order to mask off a painting area, as shown in Figure 7. Primer was applied, and allowed to dry for 24 hours. The primer was a two-part epoxy primer that required mechanical agitation, and was applied using a wet coating thickness gauge to a thick-

ness suggested by the manufacturer. The primer adheres very well to metal, in addition to paint.



Figure 7: LPR corrosion sensor ready for coating.

After the primer was allowed to dry, the paint was applied over it, again checking with a wet coating thickness gauge to ensure a proper coating layer thickness. A final coated LPR corrosion sensor is shown in Figure 8.

Next, the LPR corrosion sensor system node was installed onto the roof of the building, and all LPR corrosion sensor system cables attached to it, as shown in Figure 9. A long serial cable was also attached to the unit; this cable would eventually run down to a junction box on the side of the building, to allow personnel to communicate with the unit at ground level using a laptop computer.

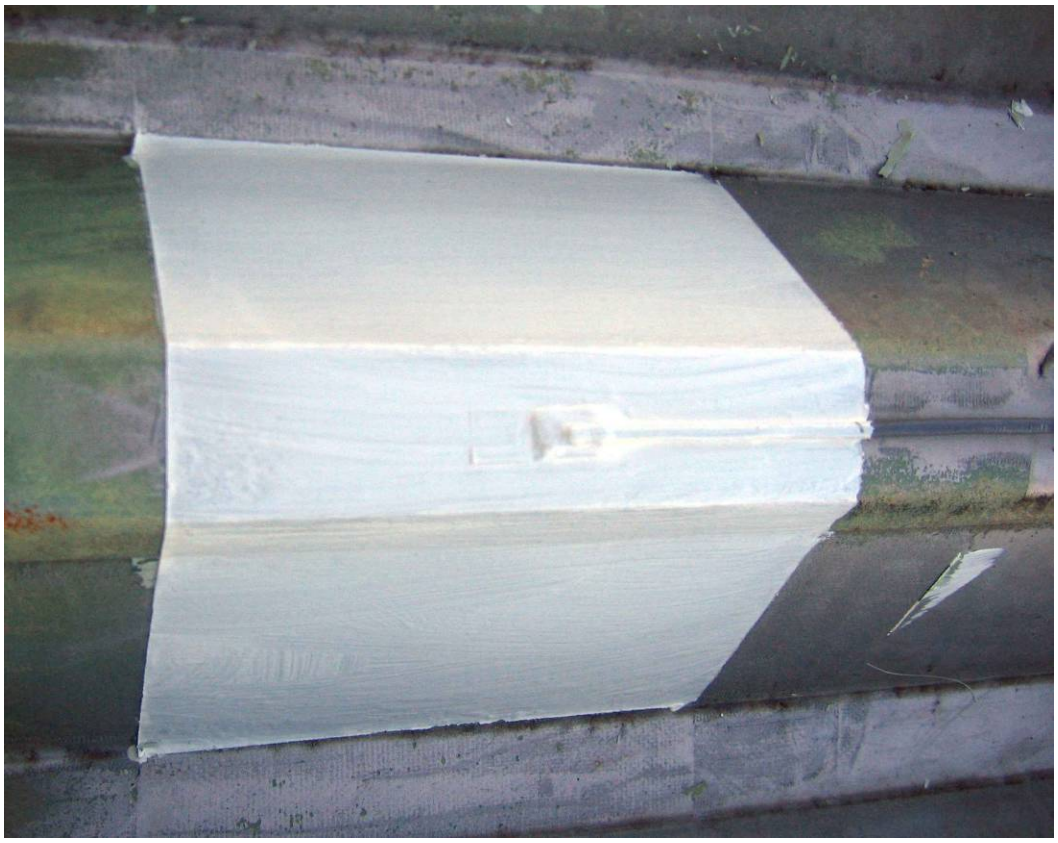


Figure 8: LPR Corrosion sensor after coating.

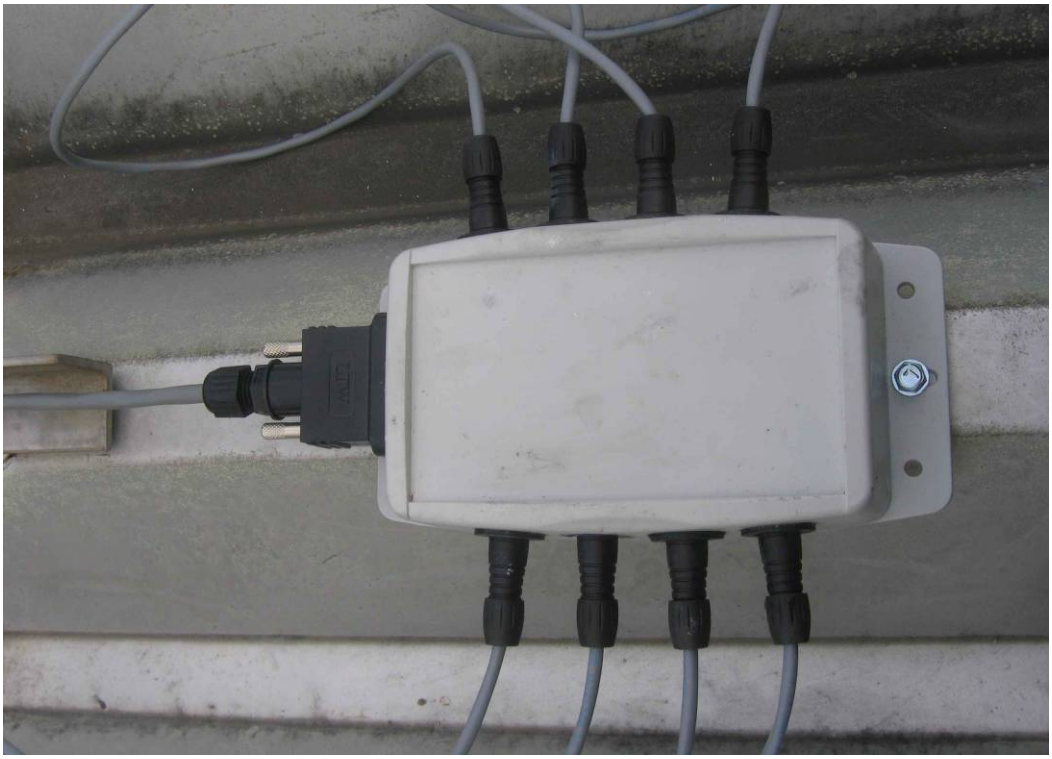


Figure 9: LPR corrosion sensor system data acquisition unit.

A junction box was then installed on the side of the building, as shown in Figure 10. The purpose of the junction box is to house the other end of the serial cable in a waterproof environment. This allows personnel the option of downloading data collected by the corrosion monitoring system on a periodic basis, if so desired.



Figure 10: LPR corrosion sensor system serial interface box.

Finally, the serial cable was run from the sensor node to junction box, and connected. The cable was securely fastened to the top and sides of the building to withstand wind forces. Using a laptop at the junction box end, the data acquisition node on the roof was queried, a series of functional tests were run, and then data collection and storage was enabled. The unit was programmed to collect and store data once an hour, for a period of over one year.

Corrosion Monitoring System Material List for Building T-270 Test Roof

Table 1: Material List Corrosion Monitoring Building T-270 Torii Station, Okinawa, Japan.

MATERIAL LIST
CORROSION MONITORING COMPARISON
BUILDING T-270
TORII STATION, OKINAWA, JAPAN

Item	Quantity	Unit	Description
01	8	Each	LPR sensor: Sensor and cable assembly, ip67 rated connectors.
02	1	Each	Monitoring tool: Model 5-603, collects sensor data and communicates with PC.
03	50	Feet	RS-232 cable: Connects monitoring tool on roof to junction box at ground level.
04	1	Each	2 part epoxy: Used to adhere sensor to roof.
05	1	Each	Denatured Alcohol: Used to clean area where sensors are to be installed.
06	1	Each	Junction box: Used to protect RS-232 cable used for monthly data downloads
07	16	Each	Strain relief: Used to hold sensor cable in place
08	1	Gallon	Paint
09	1	Bag	Large zip ties: Used to run RS-323 cable to drain pipe
10	1	Bag	Small zip ties: Used to attach sensor cables to strain relieves.

Appendix H: Calculation of Corrosion Rate From Sensor Data

Corrosion occurs when a metal or alloy is exposed to any fluid of sufficient oxidizing power. In Figure 1 Appendix B, we see a corroding device that gives good signal levels. At the interface, metal ions will escape from the metal surface leaving a surplus of electrons. This excess electron flow, from the anodic sites on the metal surface (where they are generated) to cathodic sites, where they are consumed, constitutes a corrosion current. This current is a measure of the loss of the metal from the surface. The corrosion current (I_{corr}) can be calculated from the linear polarization resistance and then used to estimate the corrosion rate. As the anodic and cathodic sites continually shift and change their positions, I_{corr} cannot be directly measured from the metal surface. A small potential drop (ΔE) has to be applied externally to induce a measurable current flow (ΔI) at the corroding surface. At given values of ΔE, I_{corr} is directly proportional to the induced current ΔI and the relationship is given as:

$$\frac{\Delta E}{\Delta I} = \frac{\beta_a \times \beta_b}{2.303 \times I_{corr} \times (\beta_a + \beta_b)} \qquad \text{Equation 1}$$

Where, β_a and β_b are the Tafel constants. The Analatom system shown in Figure 2 Appendix B is effectively a multiplexed potentiostat used to change the potential on the metal surface in a controlled manner so that the corresponding current values can be measured as a function of the potential. The relationship between ΔE and ΔI is linear at values of ΔE close to that of the equilibrium potential (E_o), assumed by the metal in absence of any induced potential ΔE. The slope of this line has the value $\Delta E / \Delta I$ and has the units of resistance. The slope is therefore called polarization resistance, R_p. The value of R_p obtained from a potential sweep over a range can then be used to determine I_{corr}, as shown by the relation above. The Tafel constants can be obtained from Tafel plots of the system under consideration. Furthermore, the rate of corrosion can be calculated from the corrosion current by using Faradays relation that correlates current flow to mass loss, given as,

$$CR = \frac{I_{corr} \times k \times EW}{d \times A} \qquad \text{Equation 2}$$

Where; CR = corrosion rate, EW = equivalent weight of the material in grams/ equivalent, k = constant, d = density, A = sample area.

Appendix I: Comparison of Wireless Technologies for Remote Monitoring of Cathodic Protection Systems

COMPARISON OF WIRELESS TECHNOLOGIES FOR REMOTE MONITORING OF CATHODIC PROTECTION SYSTEMS

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ABSTRACT

Impressed current cathodic protection (CP) systems for water storage tanks must be periodically tested in order to ensure proper performance. Wireless remote monitoring technologies provide the ability to monitor CP system performance data from remote locations using modem-equipped personal computers. Data can be provided to a central location through an existing supervisory control and data acquisition (SCADA) systems or through other wireless monitoring systems that can be installed economically. The technology provides capabilities to remotely monitor the cathodic protection system's current and "instant-on" and "instant off potentials," allowing allowed continuous monitoring of CP systems from a central location, and provide personnel with immediate warning of potential corrosion hazards.

Case studies are presented for three Army Installations and one Air Force Installation, each with different approaches to remote monitoring of cathodic protection systems for potable water storage tanks and buried pipelines. The benefits of implementation of remote monitoring are the cost avoidance of traveling to remote sites to check each rectifier, and the added capability of instant notification of a malfunction in the cathodic protection system, thus increasing the life of the structures being protected.

KEYWORDS: impressed current, cathodic protection, ceramic anodes, remote monitoring, SCADA

INTRODUCTION

Many Military Installations are spread over large areas and have many water storage tanks that use corrosion protection systems known as “cathodic protection (CP)” systems, which protect the internal or “water-side” of the tank. The outer surfaces of underground pipes, such as water, or gas distribution systems, also must be protected from corrosion in the soil using similar CP systems. In either case, CP systems need to be monitored in order to make sure that they are providing enough voltage and current to maintain the cathodic protection.

Impressed current CP systems work by connecting an anode to the structure, and applying a negative potential to the structure and a positive potential to the anode through a current from an external source, controlled by a rectifier. In recent years, ceramic-coated anodes, usually made by depositing mixed metal oxides onto titanium substrates, have been used as an alternative to the silicon-iron and graphite anodes. The ceramic anode makes corrosion protection available at much less than the life cycle cost of previous technologies and in a size-reduction that permits installation in areas previously too small.

Current cathodic protection monitoring procedures require highly skilled engineer/technician personnel and are extremely burdensome for the maintenance staff. These procedures are often deficient, and do not identify all areas where corrosion protection is either inadequate or non-existent. Furthermore, these locations generally increase with time and remain undetected, until structure perforation and failure. (CP) systems for water storage tanks must be periodically tested in order to ensure proper performance.

REMOTE MONITORING TECHNOLOGY

Remote monitoring technology [1,2,3,4] allows “on-demand” monitoring of CP systems: (1) from a central location, such as the Office of the Chief of Operations & Maintenance (O&M), or (2) from out in the field by simply driving within 1,000 feet of the CP monitoring station for a given cathodically protected structure, whereupon the CP system status information is instantly up-loaded into a portable computer or personal digital assistant (PDA), and will provide personnel with immediate warning of potential corrosion hazards.

Historically remote monitoring of cathodic protection levels has undergone several evolutions. In the 1980's a system using ground transmitters and receivers placed in aircraft that routinely flew over the pipeline for inspections was promoted. The fly-by system proved uneconomical and ineffective due to communications frequency issues, low transmitter power, and the cost of the monitoring hardware. The remote monitoring systems in use today are: (1) cellular telephone based systems, (2) Supervisory Control and Data Acquisition (SCADA) based systems, and (3) "drive-by" remote monitoring units. These remote monitoring systems both greatly increase the accuracy, frequency, and number of monitoring locations to assure that complete protection is maintained on all the protected structures. Remote monitoring systems also automate the data storage and analysis to identify any areas needing remediation and repair before any significant corrosion occurs.

CASE STUDIES

Case Study 1: Cell Phone Based Remote Monitoring at Army Installation #1

Remote monitoring units (RMUs) installed on two elevated water storage tanks at a large Army Installation in the Southwest. They are identified as Structure #1- 1.5 MMG Elevated Water Tank, and Structure #2– 2.0 MMG Elevated Water Tank. It was anticipated that any Pentium based system with at least 64 Mbytes of RAM, 5 Gigabytes of unused hard drive capacity, 56K modem directly accessing commercial telephone lines and using Microsoft's Windows 95, 98, NT or 2000 would be sufficient (later to include Windows XP) for the projects needs. Each of the two water tank sites was visited and basic data gathered regarding the cathodic protection system operating parameters. These data are shown in Tables 1 and 2. It should be noted that although the cathodic protection system on the Tank #2 was behaving somewhat erratically, it appeared to be providing effective corrosion protection to the tank.

Based on the photos and site inspection, it was determined that the RMU for the Tank #1 could be installed directly on or adjacent to the CP Rectifier unit mounted on the tank support leg, while the other RMU for the tank #2 would be mounted either inside on the exterior of the equipment building in which the CP

rectifier was installed at the RMU contractors preference. (See Figures 1a and 1b). Two prospective manufacturers were identified as having relatively inexpensive RMUs (less than $1000/RMU equipment cost) with the desired operating parameters. These parameters are shown in Table 3.

TABLE 1. CATHODIC PROTECTION SYSTEM BASIC DATA FOR WATER TANK #1

Structure 1	1.5 MMG Elevated Water Storage Tank	
AC Input	120V/60Hz/1phase - 3.37A	
DC Volts Max.	30	
DC Amps Max.	8	
Current Output Shunt Rating	100 mV = 10 Amperes	
Operating Data	Rectifier Meter	Test Meter
Volts:	2.1	2.149
Amps:	0.15	1.5 mV where 10 mV = 1 Amp
IR Free Potential (mV):	-980	-980
Potential Set Point (mV)	-980	
"On" Potential (mV):		-1151
Note: This unit is a single circuit unit with no separate riser protection circuit		

TABLE 2. CATHODIC PROTECTION SYSTEM BASIC DATA FOR WATER TANK #2

Structure 2:	2.0 MMG Elevated Water Storage Tank	
AC Input	120V/60Hz/1phase - 3.37A	
DC Volts Max.	30	
DC Amps Max.	8	
Current Output Shunt Rating	100 mV = 10 Amperes	
Operating Data	Rectifier Meter	Test Meter
Volts:	1.8 - 1.9	2.149
Amps:	0.02 - 0.03	0.0 mV where 10 mV = 1 Amp
IR Free Potential (mV):	varied -969 to -987	-980
Potential Set Point (mV)	-978	
"On" Potential (mV):		-1028
Note: This unit has a rheostat controlled secondary output circuit to protect the riser pipe		



Figure 1a – Elevated 2 MMG potable water storage tank at Army Installation #1.



Figure 1b – Typical RMU installed on water storage tanks at Army Installation #1

TABLE 3. RMU OPERATING PARAMETERS

Characteristic	Description of Requirement
No. of Data Monitoring Channels	2
Ampere Monitor	mV drop across rectifier current shunt with resolution of 0.1 millivolt and minimum RMU channel input impedance of 1 megohm.
Voltage Monitor	Voltage at output terminals of Rectifier with resolution of 0.1 volts and minimum RMU channel input impedance of 1 megohm.
Structure to Electrolyte Potential	Ability to measure both "On" and "Instant Off" potentials using existing permanently installed reference electrode with resolution of 1 millivolt and minimum RMU channel input impedance of 10 megohm.
Options	With 2 monitoring channels, choice would have to be made as to whether (1) system voltage and amperage would be monitored or (2) system amperage and structure to electrolyte potential would be monitored
Installation requirements	System would have to be furnished and installed complete by the same supplier.

The RMU chosen for installation communicated by cell phone modems with two channels of data acquisition plus the control channel. It was considered preferable to be able to measure all three parameters of CP system operating voltage, current and potential (both "On" and "Instant-Off"). The cell-phone based RMU hardware and its software were installed and commissioned at Tank #1 and Tank #2. It took over 6 hours to complete the first installation (including gaining familiarity with local telephone communications

requirements), but only 3 hours to complete the second installations and even less time for the software installation including setting parameters for site identification, data acquisition, values to be measured, and alarm limits for each channel.

Data accuracy was determined by simultaneously acquiring data using the RMUs and personnel at each site using a precision voltmeter at each site to measure the same data. As can be seen from the data in Table 4, the accuracy of the system during the initial field tests was extremely good and well within the 2% accuracy limits set by the specifications. It should be noted that there were some communication problems with the Tank #2. This occurred due to problems with the telephone company and were immediately resolved by re-setting the RMU at the site. The ability to "log" data on a continuing "real time" basis was also demonstrated

TABLE 4. RESULTS OF POST-INSTALLATION RMU TESTING

Site	Parameter	Voltmeter Value	RMU Value
Tank 1	Current (in amperes	0.28 - .30	0.28 – 0.29
Tank 1	Potential "On" (in -mV)	1.140 – 1.145	1.140 – 1.140
Tank 1	Potential "Instant Off" (in -mV)	0.970 – 0.980	0.960 – 0.980
Tank 2	Current (in amperes	0.04 - 0.04	0.04 – 0.04
Tank 2	Potential "On" (in -mV)	1.063 – 1.097	1.050 – 1.145
Tank 2	Potential "Instant Off" (in -mV)	0.970 – 0.980	0.960 – 0.980

Case Study 2: SCADA Based Remote Monitoring System at Air Force Installation

Many military Installations use Supervisory Control and Data Acquisition (SCADA) systems (5) to monitor water levels in potable water storage tanks and to monitor the performance parameters of sewage lift stations.[5] The SCADA system is wireless; it transmits its data to a central control and monitoring station and receives control signals via radio frequency transmission. Control information for the water pumps and sewage lifts station can also be transmitted to the equipment from a central location through the SCADA.

One U.S. Air Force Base in the Southeast is already monitoring impressed current cathodic protection (ICCP) systems on 4 of 5 elevated water potable storage tanks using their existing Supervisory Control and Data Acquisition (SCADA) system. By installing 3 new deep well anode beds, the number of rectifiers in the CP system for underground pipes will be reduced from 40 to 20. The AFB existing SCADA system will be extended by installing 20 additional SCADA transmitting stations at a cost of $10,000 each, at the locations where the 20 additional rectifiers will be installed and they will be interfaced to SCADA units. The SCADA system will transmit the CP data to a central location upon request. The SCADA also provides control of the rectifiers, from a central location at any given time.

The staff has utilized the services of their SCADA system sole source supplier to implement the first CP monitor system at their base on an elevated water storage tank. A schematic diagram of the SCADA based system is shown in Fig. 2a-d. This system can automatically read the rectifier voltage, amperage and the structure potential at the SCADA location. The SCADA Transmitter broadcasts line of site to an antenna on top of a water tower. The signal is re-broadcast to the main SCADA system and then can be stored in and displayed on computers in maintenance staff offices.

A typical SCADA system and cathodic protection system rectifier are shown in Figures 3a and 3b. The rectifier fine control taps are serviced by relays on the SCADA control board, which allow fine voltage control. The rectifier potentials are read directly from the rectifier into the SCADA electronic board. Also, a Hall Effect device (Figure 3b) provides rectifier current readings to the SCADA. From this “proof of concept” system, the Air Force Base has successfully replicated the first system at 3 other water tank locations



FIGURE 3a – SCADA system to which CP data acquisition system is interfaced at a USAF Base. Note antenna for wireless transmission of data.



FIGURE 3b – Typical rectifier for CP system installed on elevated water storage tanks at a USAF Base.

CP data will be stored in the Air Force's Geographical Information System (GIS) database and be accessible through standard USAF GeoBase software. The SCADA system will allow condition based display of data at a central location to allow for graphical display of any CP problems within the GIS. For example, a point with questionable readings could be made to display the problem in yellow or red indications. Analysis software in the GIS will provide the capability to visualize any utility infrastructure endangered by a failure of the CP system. For example, a user could click on a "bad" point and see a display highlighting portions of the utility infrastructure at risk, along with an explanation of system maintenance needs.

The cost of implementation of the SCADA based CP monitoring/control system is very different for locations where existing SCADA already exists versus those locations where such is not the case. For example, at their water storage sites, this AF Base already has a SCADA to control the water level in each tank and to turn various pumps on and off. However, it will cost $10,000 per location to install the SCADA at locations where it does not currently exist.

The only method the USAF Base has for monitoring test stations is by hard wiring the test station leads back to the nearest SCADA system. They have acknowledged that currently, this limits them to measuring only test points within a few hundred feet of the SCADA system. They have also ex-

pressed concerns that with the fact that these systems are limited to line of site radio frequency (RF) transmissions, and that in some cases the RF signals are attenuated by leaves on trees during the summer, in which case no CP data can be transmitted.

Case Study 3: Drive by Remote Monitoring Units at Army Installation 2 and Army Installation 3

Army Installation 2. At a second Army Installation, impressed current cathodic protection (ICCP) rectifiers and groundbeds were installed on one natural gas main, one steam main, one water storage reservoir, and three separate water supply mains. Selection of sites for ICCP installations included input by the Directorate of Public Works staff. This project demonstrated and implemented 6 deep anode impressed current cathodic protection systems (ICCP), 106 drive-by type remote monitoring units (TSDMU) for existing test stations, and 26 drive-by type remote monitoring units (RDMU) (See Figure 4) for existing and new rectifiers. Also, impressed current CP rectifiers and groundbeds were installed on one natural gas main, one steam main, one water storage reservoir, and three separate water supply mains. The six new rectifiers and deep anodes are capable of providing their full rated current output of 30 Amperes DC.

Based on the results of problems with cell phones and expense of installing the SCADA systems, the “drive-by” remote monitoring units (RMU) were installed at Army Installation 2. They were buried in the ground at about 200 impressed current CP monitoring stations. The units were programmed to “wake up” once a month, whereupon they transmit CP data using a low power RF signal. During the time window that the drive-by RMUs are transmitting, CP system maintenance personnel drive by within 0.1 mile of the remote monitoring points, guided by a global positioning system (GPS) map displayed on a laptop or PDA. Since each RMU is tied into the GPS, it broadcasts its location along with its data to the PDA. Once back in the office, the operator can down load the data into a computer where the CP files are stored and further trending analysis can be performed.[6]

The contractor who maintains the ICCP systems said that previously it would take him 2 months to obtain readings from the 106 ICCP test stations and 26 rectifiers that supply the cathodic protection current for necessary corrosion protection of those utilities. Now he can accomplish the same task in 2 days, with automated data saved in a format that allows him to establish trends for early signs that there may be a problem with the system that needs immediate attention.

Army Installation 3. At a third Army Installation, a similar drive-by remote monitoring system was implemented for a new state-of-the art ICCP system on natural gas piping, which included the use of a self-monitoring, self regulating constant output DC power supply energizing ceramic tubular shaped energy emitters (commonly referred to as cathodic protection anodes) buried deep into the earth (deep anode beds). In addition, the drive-by remote monitoring units were implemented for an ICCP system installed in a new 2 million gallon elevated water storage tank, which is this Installation's only source of potable water.

The battery operated remote monitoring system uses 10 – 15 year life replaceable batteries. Installation maintenance personnel drive through the Installation once a month with a standard PC portable computer connected to a small radio transmitter/receiver with a magnetic antenna temporarily mounted on a pickup truck roof (see Figure 5). A GPS unit monitors both the vehicle location and shows all 106 monitoring points distributed around the base on map displayed on the PC screen. Six of these monitor locations measure the output of the six DC power supplies used to energize the ICCP systems, while the other 100 units monitor the corrosion control effectiveness at key locations throughout our buried gas piping system throughout the installation. It is anticipated that it will take as little as 2 hours to accomplish the entire ICCP survey, compared to the 5-10 days that it would take for a trained technician's time to do the same work. As an additional benefit, the data is then automatically transferred in to an Excel spreadsheet where it is automatically analyzed on a "pass/fail" basis.



FIGURE 4 – (Left) Typical Pipe Protection Remote Monitoring Units Installed to Interrogate the Pipeline and Transmit System Corrosion Control Effectiveness Data. (Right) Remote Monitor Unit with Cap Removed Showing Terminal Connection Points.



FIGURE 5 – Army Installation personnel can use laptop PC to automatically interrogate and record CP protection levels while being driven by each monitoring station.

At both of these installations, for the rectifier sites where no existing SCADA exists (e.g., at rectifier units protecting piping, well casings, etc.), the SCADA would have to be installed first which had an estimated cost of $10,000 per location. This makes the system uneconomic at this Army Installation. As the CP systems only require monitoring once a month at Army Installations #2 and #3, it has been confirmed that personnel can obtain data for the same number of points at a cost of less than $12,000 annually.

Given that these Army Installation have more than 100 monitoring points where no existing SCADA is located (and where none is anticipated to be required for other measurement purposes), the “drive by” system is currently the only economically justifiable system available for automating the data acquisition and recording process

In some cases, direct burying of CP Test Station and monitor unit with 15 year nominal battery life at select locations is possible to prevent damage by normal grounds maintenance work particularly including lawn mowing work. These locations would be “marked” by easily locatable “magnetic” sensors. Implementation of “Drive by” Test Stations that can automatically acquire and transmit both “On” and “Instant-Off” potentials without interrupting impressed current CP system rectifier(s). A further development may allow the measuring of polarization decay where the -850 mV potential criteria is not being satisfied (this is under current development but

may or may not be ready during the time of this project implementation, and would not require any new hardware (only software download into CP system test station units).

COMPARISON OF WIRELESS CORROSION MONITORING TECHNOLOGIES

Hardwired RMUs for CP systems require running miles of wiring between the central control system to each monitoring station, and are not practical for military installations. In cases where the SCADA system is not a viable option, cell phone based RMU systems are best used when it is not practical or cost effective to use drive by systems, or when the data must be taken more often than once a month. For example, a remote location many miles way from the central monitoring station would constitute a hardship for maintenance personnel to drive by the location to acquire data. Of course, in order to use the cell phones, it must be established that the cell phone signals for these systems are highly reliable in those locations.

Satellite-based systems provide another alternative. They can usually provide CP data readings anywhere and at anytime through the Internet. Their initial cost is only about $500-$700 per location, but the data cost per reading per location is generally $5-$10. For a large number of locations to be monitored, this fee could become rather expensive. Also, the satellite based systems are limited to line of site. If a small number of remote locations are to be monitored, the satellite-based monitoring systems may be suitable, however, if a very large number of locations need monitoring, the satellite monitoring system may not be cost effective. A comparison of the attributes of each system is presented in Table 5.

TABLE 5. COMPARISON OF REMOTE MONITORING TECHNOLOGIES

	SCADA-Based System	**Drive-by System**	**Cell phone-Based System**	**Satellite Based System**
Initial Cost	$10,000 per monitoring station	$2,000 per monitoring station	$2,000 per monitoring station	$500-700 per station
Maintenance Requirements	Moderate	Low	Low	Very low
Complexity	High	Low	Low	High
Advantages	-Takes advantage of existing wireless system -can take readings at any time -can control remotely from a central location at any time -can interface with GIS system	-Low installation cost - can easily be installed - broadcast frequencies are pre-approved	-Low installation cost - can easily be installed - can take readings at any time - broadcast frequencies are pre-approved - can control remotely any location at any time	-Monitor CP system virtually anytime, any where in the world through the internet
Disadvantages	High cost -Signal path must be properly planned for adequate transmission – Signals must be line of site (LOS) -Signals are sometimes lost if there are impediments to LOS -FCC approval is needed for new SCADA frequencies	-Can not monitor from central location; must drive by within 0.1 mile of monitoring station	-Cost of cell phone services -Cell phone signals are sometimes lost in certain locations	-Charges fee/reading/location -Line of site limitations
Recommendation	-Use where existing SCADA system is available, such as water tanks -Do not install additional SCADA systems	-Use where there are no existing SCADA systems -Use when drive by systems are viable	Use where there are no existing SCADA systems -Use where drive by systems would not be viable- very remote areas	Use where there are no existing SCADA systems -Use where drive by systems would not be viable- very remote areas

CONCLUSIONS

The benefits of implementation of the RMUs along with upgrade of CP systems are the cost avoidance of traveling to remote sites to check each rectifier and test station, and the added capability of instant notification of a malfunction in the cathodic protection system. If SCADA systems are already available where the RMUs are to be installed, then the CP monitoring systems should be interfaced to the SCADA system. If the SCADA system is not readily available, either cell phone-based systems, satellite downlinked data systems, or drive-by systems should be implemented. The choice of whether to use cell phones based systems or drive-by systems depends on the reliability of the cell phone signals at those particular locations. By implementing remote monitoring for cathodic protection and ceramic anode-based impressed current cathodic protection systems, the life of the tank, water distribution, or gas system is expected to be extended by 30 years, while reducing the work load of Installation maintenance personnel.

Based on the results of these projects, recommendations are being provided for revisions to Unified Facilities Guide Specifications (UFGS) 13111A “Cathodic Protection System (Steel Water Tanks)” and UFGS 13112A “Cathodic Protection System (Impressed Current).” These revisions include the specifications and instructions for installing the advanced impressed current cathodic protection systems in conjunction with the “drive-by” remote monitoring units for cathodic protection systems.

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Appendix J: Wireless Connection for LPR Sensor Data Transmittal

Analatom LPR Sensor System with wireless communication

The current sensor node installed at Torii communicates serially over RS-232 with a PC running data collection software. To download data collected by a group of nodes, an operator must take a laptop with a serial port and go from node to node, connecting a serial cable to each unit and querying it for its stored data. In order to make it easier to monitor the nodes and collect data from them, hardware and software was designed and developed in the lab to enable the user to wirelessly communicate with each node. A daughter card, containing a wireless transceiver, was designed to attach to the existing sensor node, and the existing sensor node was modified to interface with the daughter card. Instead of climbing to the roof of a structure, a user within sufficient range of the sensor nodes will be able to communicate with each node as if the nodes were physically connected to the PC.

The type of wireless network designed is based on the ZigBee standard. This is a wireless technology developed as an open global standard to address the unique needs of low-cost, low-power, wireless sensor networks. The standard is based upon the IEEE 802.15.4 physical radio specification, and operates in unlicensed bands worldwide at the following frequencies: 2.400–2.484 GHz, 902-928 MHz and 868.0–868.6 MHz.

This technology has ultra-low power consumption promoting a long lifetime for battery-operated devices. ZigBee networks are designed to conserve the power of the slave nodes on the network. For most of the time, a slave mode is in deep-sleep mode and wakes up only for a fraction of a second to confirm its presence in the network.

Another key component of the ZigBee protocol is the ability to support mesh networks. In a mesh network, nodes are interconnected with other nodes so that at least two pathways connect each node. Connections between nodes are dynamically updated and optimized to work under difficult conditions. In some cases, a partial mesh network is established, with some of the nodes only connected to one other node.

Mesh networks are decentralized in nature; each node is self-routing and able to connect to other nodes as needed. The characteristics of mesh topology and ad-hoc routing provide greater stability in changing conditions or failure at single nodes. This results in a robust, stable network.

Since the mesh network topology is very robust, it is clear that the wireless solution designed should include the ability to easily support mesh networks. That and the requirements for low-power consumption and small form factor lead to the choice of a ZigBee-based product.

This wireless base station that communicates with a PC (either serially or otherwise) will be provided in the continuation of this project. The data collection software will communicate with this base station, which in turn will communicate wirelessly with each sensor node. In this manner, the user can communicate with the sensor nodes remotely, from an office or vehicle within range of the sensor array. Follow on testing on this wireless method is planned for the next phase, including the upgrading of capabilities to link via satellite. This is discussed in the “Recommendation” section.

Appendix K: Possible Applications of the Corrosion Monitoring System

Building metal roofs and air conditioning systems

Besides on roofs as demonstrated on this project, the LPR Corrosion Sensors could also be used to monitor and evaluate the new coatings being applied to protect air conditioning systems against corrosion. This is suggested for parts of the air conditioning system that are not easily accessible for visual inspection. Using the wireless implementation all the Torii Station buildings air conditioning systems could be monitored from a console placed in one location thereby obtain warning for early less costly repairs and also maintenance cost savings due to significant savings of manpower inspection time.

Communication dish stalks

The dish antennas that were inspected at Torii have recently been overhauled and coated. They provided an excellent window into the onset of corrosion on the structures. Corrosion initiation sites are already clearly visible. Despite the relatively new coating, any area that has been exposed to any form of wear or metal particle contamination seems to suffer virtually instant corrosion.



Figure 1: The hub of the dish is located on the edge of the stalk and difficult to access for inspection

All the dish stalks fittings and boons are fitted with access points, but these do not allow visual inspection without specialist equipment. An example is given in Figure 1, where we see an access hole leading into a support pylon. Specialist equipment such as an endoscope would be needed to inspect such locations for corrosion. Such scenarios offer an excellent opportunity for sensing corrosion using the LPR Corrosion Sensor technique.

Where the components are visible and not safety critical their deterioration can be monitored visibly and components can be replaced. In other locations where access is limited the components can be effectively monitored using sensors. On some of the main framework of the antenna, corrosion is already in an advanced state. This section of the structure was on the back of the main dish. It was difficult to access and inspect and had probably not been properly coated. LPR Corrosion Sensors could also monitor such areas.

Fencing

The fences on the perimeter of the base, and inside base to enhance security of sensitive areas represent a significant financial investment. All fences are made from galvanized steel. On the fences inspected the zinc coating protects them well in the first few years of use.



Figure 2: The relative corrosion rate of stainless steel and galvanized steel is striking, but stainless steel fences are economically unpractical at ten times the cost of galvanized steel

In terms of LPR Corrosion Sensor application, the uses are limited. The deterioration of the fences is reasonably evenly spread and visual inspection near the end of the fences life is sufficient to determine if the fence needs replacement.

LPR Corrosion Sensors could be used to measure the background corrosion rate in an area and advise that a remote fence needs inspection. This is particularly applicable nearer the ocean where accelerated corrosion rates cause fence fixings to corrode at greater rates. LPR Corrosion Sensors on the fence fixings could warn of this phenomenon and alert engineers to inspect and replace the failing components.

Metal buildings

There are numerous metal buildings used on the island by the US military. The buildings are favored as they are quickly constructed and fair well in Typhoons. Due to the high corrosion rates on the island, these structures tend to suffer from severe corrosion.

Metal buildings that are not maintained to a high standard pose a number of safety hazards. In particular, the risk of overhanging structures collapsing poses a health risk as well as a financial risk of damage to operations or stored equipment. An excellent example of safety issues is the complete overhang structure. Failure of such structures posses a real risk to human

life. Inspection of the structure showed that its interface to the main building was not a continuous joist, but a bolted-on section. The condition of the interface could not be ascertained as it was too remote to view without the appropriate scaffolding. This sort of interface posses an excellent application for LPR Corrosion Sensor sensing technology, where we have a safety critical, high value structure that is difficult and expensive to inspect and suffering aggressive corrosion.



Figure 3: Safety critical buildings suffer degradation due to corrosion and are neglected

Metal containers

On more detailed inspection of Torii Station and the surrounding bases it was clear that there are a significant amount of shipping and storage containers used by the U.S. military on the island. These containers appear to be completely overlooked despite the fact that they represent a significant capital investment. Inspection of these containers shows some corrosion is rife all over the structures. In Figure 4 we see that interfaces between doors and locking gear have completely failed. This failure on the door interfaces was common to nearly all the containers inspected. These con-

tainers are not double skinned; as such, the contents are exposed to the elements once the outer skin has failed.

Container monitoring also offers an excellent opportunity for using LPR Corrosion Sensors as generally the structures are not inspected or well maintained and failure is an expensive and mission inhibiting event. In the case of containers, sensors can be fitted inside the structure along the doors and on the roofs. Any failure of the container, e.g., exposure of the inside to the elements can be instantly monitored and appropriate warnings generated to protect the contents of the container. This scenario may also offer the best ROI as the systems are easily fitted and maintained, and, military containers tend to hold high value contents such as ammunition or weaponry.



Figure 4: The containers tend to corrode at the bottom, on hinges and on their roofs

Fire containment water supply pipes (for fuel dumps)



Figure 5: In some cases, the corrosion has been so severe that the pipe has failed

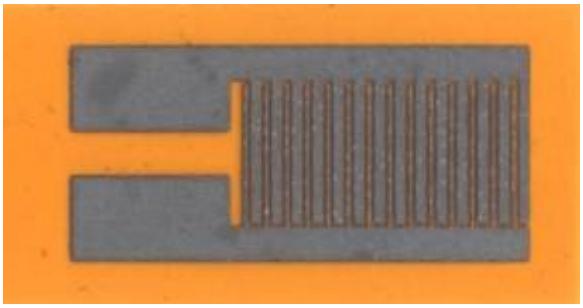
As the U.S. military presence on the island is that of a forward post there are significant fuel supplies on the island. These represent the reserves that would be used in any conflict and must be well maintained. All of the supplies have a fire suppression system that consists of 6" bore piping providing water to automatic water jets. An elaborate piping system supplies all of these water jets.

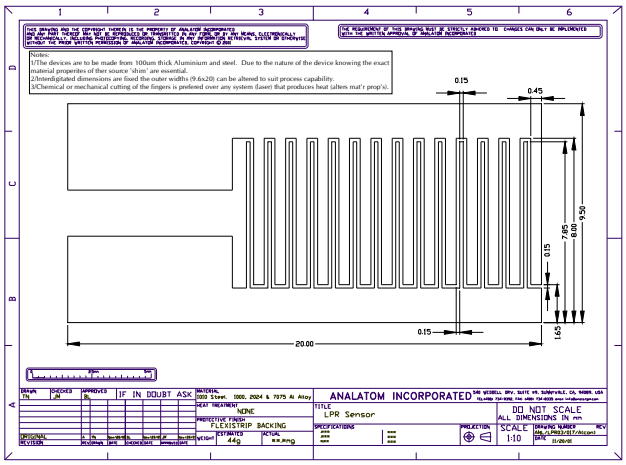
As there is no pre-requisite to define corrosion locations, the only effective method of monitoring corrosion on the pipe in all areas is to have a high sensor density. Considering that high sensor densities relate to higher costs, a detailed ROI calculation has to be performed in order to recommend this application of the LPR Corrosion Sensors.

Appendix L: Specifications for LPR Corrosion Sensors and Monitor

Model 1010-150

Linear Polarization Resistor





The Analatom Inc. corrosion sensor is a Linear Polarization Resistor (LPR) that works on the same principle as macro LPR systems do. It is a device that corrodes at the same rate as the structure on which it is placed. The sensor is made up of two micro machined electrodes that are interdigitated at 150µm apart. The corrosion reaction – both oxidation and reduction – produces a corrosion current that can be pre determined empirically for each sensor type, this I/V (Current/Voltage) form is called a Tafel plot.

The sensor itself is made from shim stock of the same material as the structure that is being monitored. The shim is usually 25µm thick (0.001”) and is attached to a Kapton backing sheet of similar thickness. This gives the sensor a total thickness in the 50µm range, although a thickness of up to 200µm is possible if required. The shim is machined (pattered) using a photolithography technique, this allows for a varied design layout so that sensors can be fitted deep into tight structures such as bridge cables and lap joints.

The sensor can be placed directly on the metal surface of the structure to be monitored. Painting and other surface preparations can be performed

on top of the sensor with no damage to the sensor or coating. In operation the sensors are unobtrusive and require no maintenance or inspection. The system that monitors the sensor is low powered and both sensors and system are robust. The system is designed to be easily installed and operated with an indefinite operating life. The autonomous battery powered version of the system can run for over a decade without need for replacement. A solar powered unit will also be available. The GUI and user interface all load onto a standard Windows PC and are easy to use and interface with other sensors and systems.

Analatom, Inc.

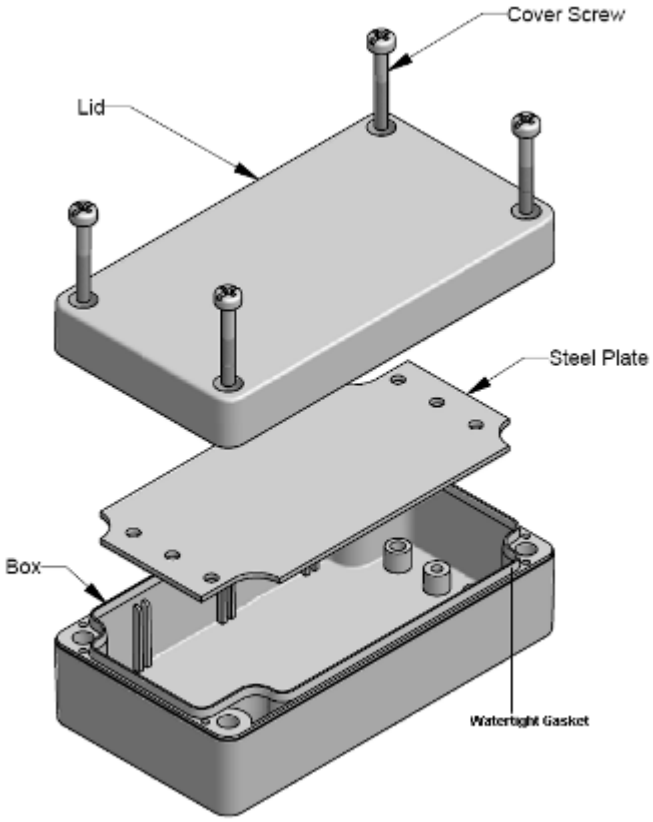
www.analatom.com | support@analatom.com

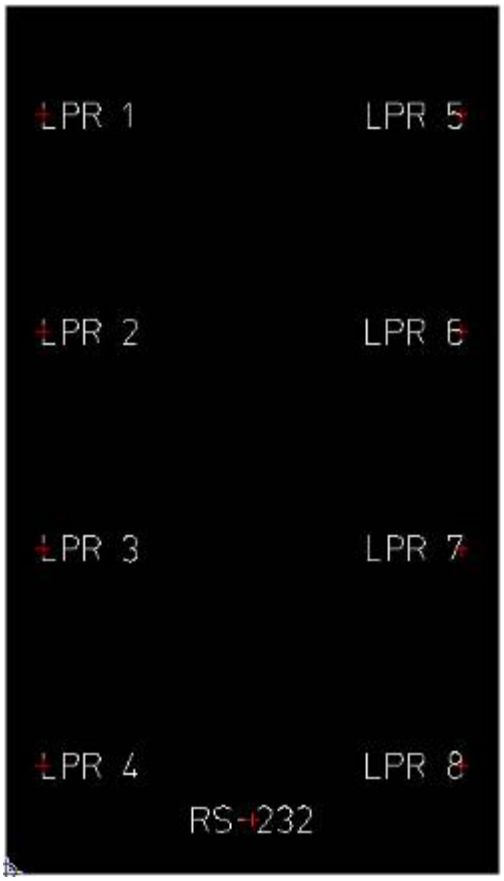
562 E Weddell Drive Suite 4 ♦ Sunnyvale, CA 94089-2108, USA.

Tel: **1 (408) 734 9392 Fax: **1 (408) 734 8335

Model 5-603

Corrosion Monitor





Sensors are connected to the Corrosion Monitor, a central data node, that processes the sensors output, stores the data and communicates serially with a PC. The node is also capable of recording data from most standard commercial-off-the-shelf sensors. The corrosion monitor can be battery powered and have a typical life of 5 years between battery changes when used for corrosion monitoring. Solar and bus powered systems are also available.

The enclosure box is a waterproof gasket, and screws will be outside of sealing area, making a reliable waterproof case.

Analatom, Inc.

www.analatom.com | support@analatom.com

562 E Weddell Drive Suite 4 ♦ Sunnyvale, CA 94089-2108, USA.

Tel: **1 (408) 734 9392 Fax: **1 (408) 734 8335

Appendix M: Health and Safety Plan

Overview

Industrial injury accidents create a no-win situation for everyone involved. Employees experience pain, suffering and incapacitation while the company suffers from the loss of the injured person's contributions. This document provides information and guidance for the establishment and maintenance of an accident-free work environment.

Procedures

Analatom directive contains guidance for safety procedures to be followed, and forms to be used. Supervisors are expected to integrate the procedures into the appropriate work activity and employees are expected to apply them on the job. The directive sample forms are to be used if they apply to the job concerned.

A copy of the statement will be issued to all supervisory and management personnel. A copy of the policy statement will give to each employee.

Regulations

A copy of the following documents will be maintained on each job site:

- Analatom Incorporated Safety Manual
- OSHA Safety and Health Standards (29 CFR 1926 - Construction and 29 CFR 1910 – General Industry)

Safety and health policy

The purpose of this policy is to develop a high standard of safety throughout all operations of Analatom Incorporated and to provide guidelines so employees are not required to work under conditions that are hazardous or unsanitary.

Employees have the right to derive personal satisfaction from their jobs. The prevention of occupational injury or illness is central to this belief that it will be given top priority at all times.

It is Analatom Incorporated's goal to initiate and maintain complete accident prevention and safety training programs. Each individual is responsible for the safety and health of those persons in their charge and co-workers around them. By accepting mutual responsibility to operate safely, we will all contribute to the well being of personnel.

Appendix N: Quality Control Plan

LPR sensor calibration

The Gamry 600 EIS Portable was used to enhance the production of the sensors. It was used to determine the Tafel Constant of new metals. Upon receiving this equipment, it was installed and a quick check out and calibration of the unit was made to make sure it was functioning properly. Figure 1 shows the calibration setup.

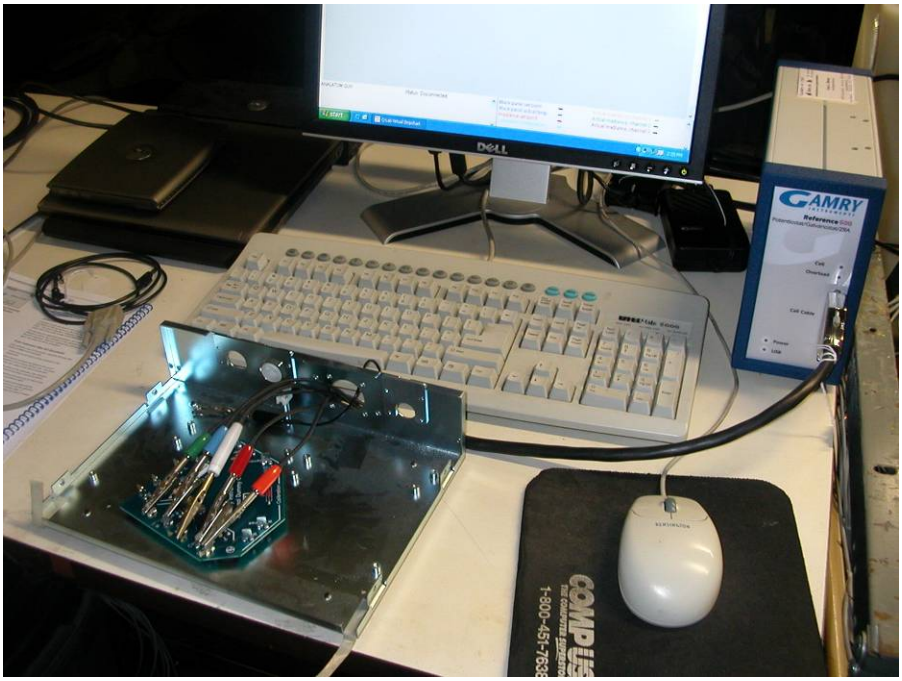


Figure 1. Gamry Calibration Setup.

Quality control

Before assembling the sensors for the experiment a quality control test was performed using a QUV Accelerated Weathering Tester chamber shown in Figure 2.

The quality control process is used to weed out malformed and malfunctioning sensors prior to sensor assembly.



Figure 2: Sensor Quality Control Test.

Sensor system production process

In order to get a good bonding to the sensors, the bonding pad on the sensors was carefully cleaned first. Sand paper was used to slightly abrade the surface of the bonding pad to remove the oxide layer to insure a strong and reliable bond. Figure 3 shows the process of making the sensors.

After finishing the wire bonding process, Figure 4, the sensors are ready to have a connector, which it connects to the corrosion monitoring unit for testing, installed.

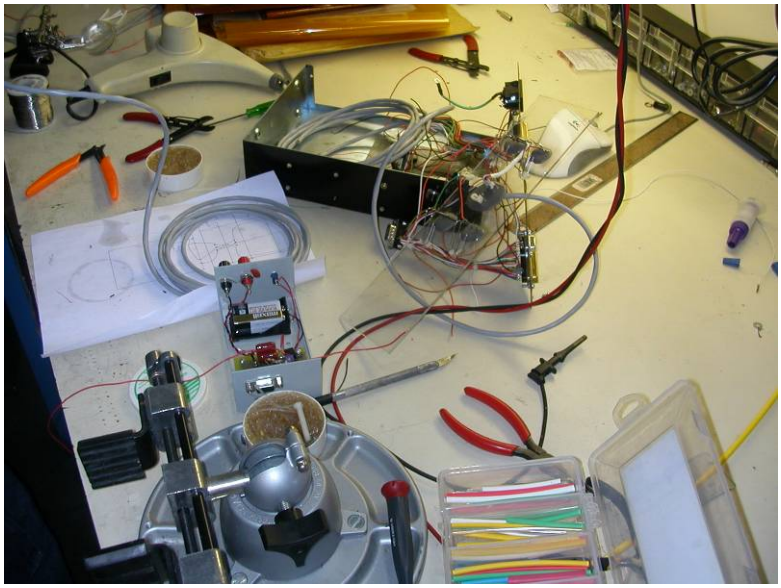


Figure 3: Attaching Wires to the Sensors.

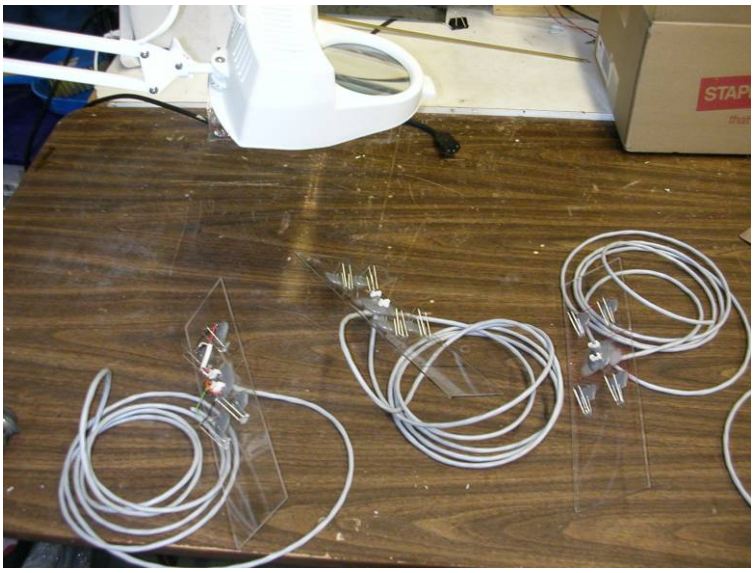


Figure 4: Sensors Are Ready to Connect to the Corrosion Monitoring Unit.

Once the sensors are done, the corrosion unit shown in Figure 5, is calibrated. This part of the quality control is to make sure everything is functioning properly. The LPR sensors can only be read with the Analatom corrosion monitoring unit. The unit electronics have been very carefully designed such that the reading does not destroy the LPR sensor. Appropriate training and processing procedure to ensure accuracy of the collected data is needed.

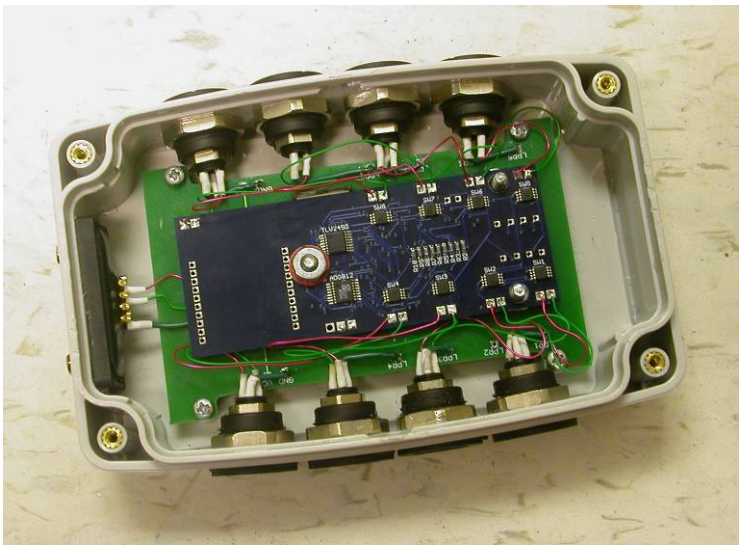


Figure 5: Analatom Corrosion Monitoring – Data Gathering Unit

Appendix O: Project Management Plan for CPC Project FAR-04

RECLAMA
FAR04: REMOTE CORROSION SENSORS FOR DETECTION OF CORROSION ON MISSION ESSENTIAL STRUCTURES IN SEVERELY CORROSIVE ENVIRONMENTS AT OKINAWA (RDT&E, FY06)

Reviewers' Questions: "Why is this a new project - what's different about this remote sensing?"

The technology described in this FY06 CPC Project Plan is a wireless postage-stamp sized linear polarization resistance corrosion rate sensor for inaccessible structures. The sensor is particularly suited to areas prone to corrosion like a "well" (or depression) in the surface where water can not drain easily, and where corrosion can initiate. These areas are not easily accessible for visual observation. This sensor technology is to be used on above-ground structures where frequent repainting is required, such as the antenna structure in Okinawa. The wireless postage-stamp sized sensor to be employed utilizes linear polarization resistance (LPR) technology, which we have validated in field tests.

The wireless postage stamp-sized sensor was developed for detection and measurement of corrosion of the underfilm surface of above-ground structures due to atmospheric corrosion. The use of this technology is expected to reduce repainting costs by predicting and scheduling repainting when it is really required and is based on a pre-selected corrosion rate criteria based on service life.

By contrast, some of the on-going Army Facilities FY05 CPC Projects, and some of the proposed FY06 CPC Projects address remote sensing of performance of cathodic protection systems, corrosion of the water side of pipes, and leak detection of water, as discussed below.

- The on-going FY05 CPC Project AR-F-321: "Remote Monitoring of Cathodic Protection Systems and Cathodic Protection Upgrades for Tanks and Pipelines at Fort Carson" involves the use of remote monitoring units to monitor the performance (voltage and current) of the impressed current cathodic protection anodes for the water-side of potable water storage tanks and the soil-side of underground pipes in order to ensure that cathodic protection is being maintained.
- The on-going FY05 CPC Project AR-F-311, "Leak Detection for Pipes at Fort Hood" uses acoustic emission for sensing of water system leaks after they occur.
- The on-going FY05 CPC Project AR-F-317, "Pipe Corrosion Sensors at Fort Bragg" uses probe-type sensors for corrosion sensing/detection in water pipes
- The proposed FY06 CPC Project FAR05 "Corrosion Detection and Management of Potable Water" involves large wired probe-type sensors to detect corrosion and water corrosivity in potable water on uncoated interior water pipe surfaces, as well as an integrated system consisting of corrosion prediction, prevention, and management for potable water systems

ARMY FACILITIES
CORROSION PREVENTION AND CONTROL PROJECT PLAN
Remote Corrosion Sensors for Detection of Corrosion on Mission Essential Structures in Severely Corrosive Environments at Okinawa (RDT&E, FY06)

TRISERVICE PROGRAM
ARMY FACILITIES

CORROSION PREVENTION AND CONTROL PROJECT PLAN

Remote Corrosion Sensors for Detection of Corrosion on Mission Essential Structures in Severely Corrosive Environments at Okinawa (RDT&E, FY06)

15 June 2005 (Revised 19 July 2005)

Submitted By:

Ashok Kumar

U. S. Army Engineer Research & Development Center (ERDC)
Construction Engineering Research Laboratory

Comm: 217-373-7235

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(Project Number to be *assigned by OSD when approved*)

ARMY FACILITIES
CORROSION PREVENTION AND CONTROL PROJECT PLAN
Remote Corrosion Sensors for Detection of Corrosion on Mission Essential Structures in Severely Corrosive Environments at Okinawa (RDT&E, FY06)

1. STATEMENT OF NEED

PROBLEM STATEMENT: Tori Station Okinawa has identified severe coating degradation of coatings on protective structures for mission critical equipment, which will eventually lead to high corrosion rates and failures. Corrosion rate measurement can reveal which areas of a structure need immediate maintenance and which ones will need maintenance later, as well as allow an optimal maintenance schedule to be developed. At Tori Air Station, the following structures need monitoring of corrosion rates:
(1) Command Control, Communications, Computer and Intelligence, Surveillance and Reconnaissance (C4ISR) Facility; (2) dish antenna for communications.
These structures are shown in Figure 1. It is estimated that about 20 additional Army Installations have similar corrosion problems. Furthermore, all Tri-service Installations have similar coating deterioration problems.

IMPACT STATEMENT: If this project is not funded, the mission critical structures will continue to corrode, due to intrusion of moisture at holidays in the coatings, eventually leading to failure. The dish antenna used for communication was repainted 18 months ago, and now requires repainting again. There is a need for sensors on these structures that can detect the onset of corrosion under coatings on mission-critical metallic structure in severely corrosive environments and provide that data to the maintenance staff, who can immediately perform corrective maintenance. If holes develop in the protective structure, mission critical equipment within the C4ISR could be damaged.

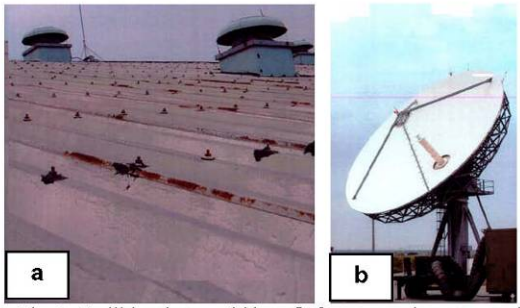


Fig. 1. Facilities that would benefit from corrosion rate monitors
a. Degrading Paint on C4ISR Facility
b. Dish Antenna that Requires Repainting

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CORROSION PREVENTION AND CONTROL PROJECT PLAN
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2. PROPOSED SOLUTION

TECHNICAL DESCRIPTION: Innovative remote sensors can provide data on corrosion status at various locations of mission-critical metal structures. The sensors can be applied to surfaces of mission-critical steel structures, and will respond to intrusion of moisture, which causes increase electrical resistance as they are affected by changes in the local corrosive environment. Corrosion rates can be predicted from the shifts in polarization resistance. Increasing corrosion rates signal the need for corrective action, such as removal of corrosion, and re-coating of the structure. The sensor to be employed is built on well-established LPR (Linear Polarization Resistor technology) and it outputs an exact corrosion rate for the structure on which it is placed. The sensor can be placed onto a structure that is stripped down to bare metal and then recoated, or on top of existing coatings that need to be overcoated.

This sensor technology has been evaluated in the laboratory and requires a field demonstration. ERDC-CERL has investigated the LPR methodology to measure corrosion rates in two 33-year field tests of steel H-pilings in seawater at Buzzard's Bay, MA and at La Costa Island, FL (See Fig. 2). Some steel H-plies were coated with various protection systems, such as coal tar epoxy, glass flake composite, polyurethane, flame sprayed zinc and aluminum, while others were left uncoated for baseline comparison. Sacrificial cathodic protection was provided by anodes to some of the bare and coated steel pilings. The LPR measurements were correlated with visual observations of the piling condition and flange thickness measurements.



Fig. 2. Steel H-pilings in 33-year field test in seawater at La Costa Island, FL, which ERD-CERL evaluated by similar linear polarization measurement-based technology, being proposed

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CORROSION PREVENTION AND CONTROL PROJECT PLAN
Remote Corrosion Sensors for Detection of Corrosion on Mission Essential Structures in Severely Corrosive Environments at Okinawa (RDT&E, FY06)

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2. V. Van Blaricum and A. Kumar, "Field Evaluation of Cathodic Protection Index for Bare and Coated Steel in Seawater," Paper No 528, CORROSION 93, National Association of Corrosion Engineers (NACE) International Annual Conference, 1993.

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4. A. Kumar, A. Beitelman, and E. Meronyk, Corrosion Control of Pilings in Seawater: Buzzard's Bay, MA" Paper No. 345,CORROSION 84, National Association of Corrosion Engineers International Annual Conference, 1984.

5. Ashok Kumar, et. al. "Coatings and Cathodic Protection of Pilings in Seawater: Results of 5-year Exposure," Materials Performance, (18,12), 1979.

Technology Maturity: The remote corrosion sensor technology herein proposed is a advanced technology, that has been tested in the laboratory, but requires field demonstration and validation in operational environments.

The technology being utilized is an advanced sensor based on an electrochemical technique called linear polarization resistance (LPR). Corrosion occurs when a metal is exposed to moisture. The moisture is the electrolyte in an electrochemical reaction. Some metallic sites become *anodic*, meaning that they have lost electrons. Other metallic site becomes *cathodic*, meaning that they have a surplus of electrons. Those electrons flow from the anodic site to the cathodic sites, constituting a corrosion current (I_{corr}). This corrosion current cannot be measured directly as anodic and cathodic sites continually change their positions and shift their potential. Therefore, I_{corr} must be measured by externally applying a small potential drop (ΔE), which induces a current, ΔI. At small values of ΔE, near the equilibrium potential, a linear relationship exists between ΔE and ΔI. The slope of a ΔE vs ΔI plot, $= \Delta E / \Delta I = R_p$, where R_p is called the linear polarization resistance. (LPR). Values of LPR are obtained from a potential survey over a range. Tafel Constants are calculated from a Tafel Plot as shown in Fig.3 by estimating the linear slopes of the cathodic and anodic currents. These constant are used along with R_p to determine I_{corr}.

Finally, the corrosion rate can be determined by the Equation:

Corrosion Rate= $(I_{corr})(F)(EW)/[(d)(A)]$

Where F= Faraday's Constant; EW= Equivalent weight for the metal; d =density of the metal; A= area of the metal over which reaction occurs (in this case the sensor)

Of course, the metal sensor must be made of the same metal as the underlying metal where the corrosion rate is being evaluated. Several sensors may be powered via electronics at the nodes. The LPR signals from the sensors are multiplexed together at the nodes and then transmitted to the main computer, where the data is collected, interpreted, and displayed. The power required for each sensor is 0.1 milliWatt. Figure 4 shows the sensors and the associated node electronics. The sensors themselves are placed at strategic locations next to the base metal (substrate) and then covered with the same coating as the rest of the structure.

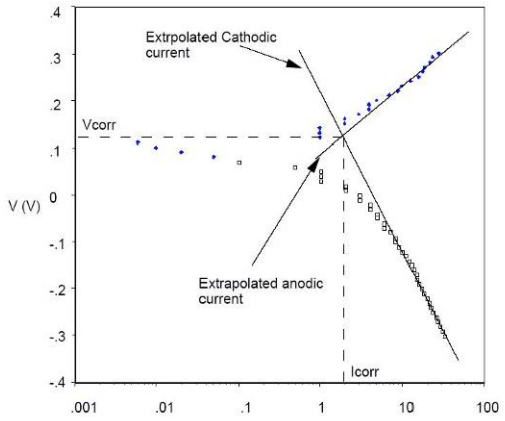


Fig. 3. Typical Tafel Plot for steel LPR corrosion sensor

Reviewers' Questions: "Why is this new project - What's different about this remote sensing?"

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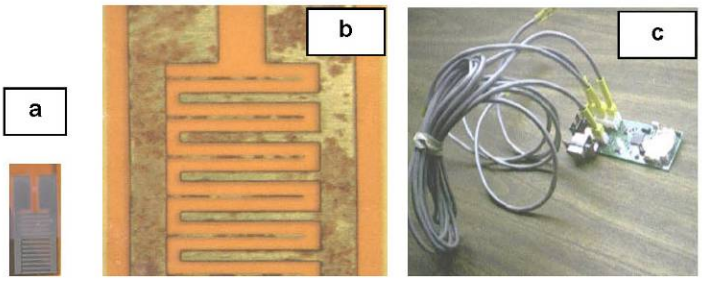


Fig. 4. Linear Polarization Resistance (LPR) corrosion rate sensor system: (a) individual sensor actual size; (b) Magnified view of 1010 steel sensor that has been subjected to a corrosive environment; (c) sensor node with electronics

RISK ANALYSIS: The risk for this project is low, as advanced technologies will be demonstrated and validated. The implementation of technologies will not be performed in phases.

EXPECTED DELIVERABLES AND RESULTS/OUTCOMES:
When this sensor is installed underneath a coating on a mission critical structure , the corrosion rate data is transmitted to a central location by a wireless radio system, where it can be conveniently monitored. The use of the corrosion rate sensors results in service life extension of the structure, and lower life cycle cost, due to early detection and correction of the problem. The sensors will be applied to mission critical structures such as C4ISR Facilities and dish antennas. These sensors will provide a means of remotely determining where corrosion is imminent and will indicate what areas need immediate attention. For example, it is possible that a mission critical structure may not need recoating when originally scheduled. On the other hand, the structure may need recoating earlier than scheduled. This sensor helps to take the guessing out of maintenance, and optimize maintenance funds.

PROGRAM MANAGEMENT
The Project Manager will be: Dr. Ashok Kumar (ERDC/CERL). The Associate Project Manager will be Dr. L. D. Stephenson (ERDC-CERL). Mr. Martin Savoie is Chief of the ERDC/CERL Materials and Structures Branch. The stakeholders will be Mr. James Leander (Okinawa Directorate of Public Works POC), Mr. Alan Carroll (IMA-PARO, Mr. Paul Volkman (HQ-IMA), Mr. David Purcell, (HQ-ACSIM), as well as Triservices WIPT representatives, Ms. Nancy Coleal (AFCESA/CESM), and Mr. Tom Tehada (NFESC).

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Customers are Mr. James Leander (Okinawa Directorate of Public Works POC) and Mr. Alan Carroll (IMA-PARO) The Army has provided matching funds for this project through HQ-IMA (See Memorandum from ACSIM Director for Facilities and Housing in Appendix 2). Coordination with the Army Corrosion Program Office will be through Mr. Hilton Mills (AMC).

This is a TriService Project. Funds have been requested for travel of Air Force and Navy representatives to participate in the evaluation of technology implementation. The approach for project performance will include use of Type I –In house, organic capabilities, and Type II Existing Contacts. A Type II Existing Contractual Agreement is expected to be utilized for this project two months after receipt of funds.

3. COST/BENEFITS ANALYSIS

a. **Funding ($K):**

Funding Source	OSD	Service Matching
Labor	200	210
Materials	150	150
Travel	50	50
Report	40	40
Air Force/Navy Participation	10	-
TOTAL ($K)	**450**	**450**

b. **Return-On-Investment Computation**

1) Useful Life Savings (ULS) is equal to the "Net Present Value (NPV) of Benefits and Savings" calculated from the Spreadsheet shown in Appendix 1 that is based on Appendix B of OMB Circular A94.

ULS= $12,628 **K** (from OMB Spreadsheet in Appendix 1. Assumptions for this calculation are also given in Appendix 1).

2) Project Cost (PC) is shown as "Investment Required" in OMB Spreadsheet in Appendix 1; **PC**= $900K.

$$ROI = \frac{ULS}{PC} = \frac{\$12{,}628K}{\$\,900\ K} = 14$$

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c. **Mission Criticality:** The benefits of the implementing remote corrosion rate sensors at on C4ISA Facilities and dish antennas include restoration of the facilities and equipment to optimum operating condition, in addition to reduced maintenance, and increased safety, increased operational readiness and reliability.

4. **SCHEDULE**

MILESTONE CHART

EVENT	TIME (months after receipt of funds)
Award Contract	2
Select sensors	4
Implement sensors	6
Implement Coatings over sensors	8
Complete installation of sensors and coatings	15
Complete Documentation (includes Final Report, Procurement Specification, Ad Fliers	18
Complete ROI Validation	18

a. Note: If project is approved, *bi-monthly status report will be requirement* (i.e. starting the first week of the second month after contract award and every two months thereafter until final report is completed). This report will be submitted to the DoD CPC Policy & Oversight office. The report will include project number, progress summary (and/or any issues), performance goals and metrics and upcoming events.

b. Examples of performance goals and metrics: include achieving specific milestones, showing positive trend toward achieving the forecasted ROI, reaching specific performance quality levels, meeting test and evaluation parameters, or successfully demonstrating a new system prototype.

5. IMPLEMENTATION

a. Transportability/Transition approach. Where appropriate, Unified Facilities Guide Specifications (UFGS), Engineering Instructions (EI), Technical Instructions (TI), and Technical Manuals (TM), including updates, will be developed. In addition, a final report describing the details and results of the project, will be submitted to OSD. The draft documents will be posted on the OSD Corrosion Exchange website under "Spec & Standards" and "Facilities Special Interest Group (SIG)." Coordination with potential users will be an essential part of the transition of the technology.

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It is the intent of the Project Management Plan (PMP) to implement this corrosion prevention and control technology at multiple regions and installations. The UFGS, EIs, TIs, and TMs, including updates to existing guidance documents, developed for Army-wide implementation during the FY06 project, will be utilized to facilitate the planned implementation of remote corrosion monitors for protective structure for mission critical equipment.

b. Potential ROI validation. The potential ROI will be validated by comparison of coated structures with and without remote corrosion monitors.

c. Final Report: A final report will be submitted within 60 days of completion of the project. The report will reflect the project plan format as implemented and will include lessons learned.

Projected Benefits:
Based on the laboratory testing and limited field testing by NASA research laboratories, the use of the corrosion rate sensors results is expected to result in service life extension of the structure, and lower life cycle cost, due to early detection and correction of the problem.

Operational Readiness
These remote corrosion rate sensors are available and ready for implementation as solutions to monitor corrosion rate due to degradation of coatings over critical military structures.

Management Support
This project enjoys the support of the Okinawa Directorate of Public Works (DPW) Office, **Moreover, the Army (HQ-IMA) has planned to provide matching funds for FY06. See attached Memorandum from ACSIM Director for Facilities and Housing in Appendix 2.**

ARMY FACILITIES

CORROSION PREVENTION AND CONTROL PROJECT PLAN
Remote Corrosion Sensors for Detection of Corrosion on Mission Essential Structures in Severely Corrosive Environments at Okinawa (RDT&E, FY06)

6. COORDINATION

ORGANIZATION	SIGNATURE	DATE
Project Manager	Ashok Kumar	6/13/05
ERDC/CERL Branch Chief	[signature]	6-13-05
Installation DPW POC		
IMA Region		
HQ IMA		
HQ ACSIM		
HQ AMC		
Tri Service Facilities WIPT Chair		

This is a TriService Project. Funds have been requested for travel of Air Force and Navy representatives to participate in the evaluation of technology implementation.

ARMY FACILITIES

CORROSION PREVENTION AND CONTROL PROJECT PLAN

Remote Corrosion Sensors for Detection of Corrosion on Mission Essential Structures in Severely Corrosive Environments at Okinawa (RDT&E, FY06)

6. COORDINATION

ORGANIZATION	SIGNATURE	DATE
Project Manager		
ERDC/CERL Branch Chief		
Installation DPW POC		12 Jun 05
IMA Region		
HQ IMA		
HQ ACSIM		
HQ AMC		
Tri Service Facilities WIPT Chair		

This is a TriService Project. Funds have been requested for travel of Air Force and Navy representatives to participate in the evaluation of technology implementation.

ARMY FACILITIES

CORROSION PREVENTION AND CONTROL PROJECT PLAN
Remote Corrosion Sensors for Detection of Corrosion on Mission Essential Structures in Severely Corrosive Environments at Okinawa (RDT&E, FY06)

6. COORDINATION

ORGANIZATION	SIGNATURE	DATE
Project Manager		
ERDC/CERL Branch Chief		
Installation DPW POC		
IMA Region	Wayne Nash	9/06/06
HQ IMA		
HQ ACSIM		
HQ AMC		
Tri Service Facilities WIPT Chair		

This is a TriService Project. Funds have been requested for travel of Air Force and Navy representatives to participate in the evaluation of technology implementation.

ARMY FACILITIES

CORROSION PREVENTION AND CONTROL PROJECT PLAN
Remote Corrosion Sensors for Detection of Corrosion on Mission Essential Structures in Severely Corrosive Environments at Okinawa (RDT&E, FY06)

6. COORDINATION

ORGANIZATION	SIGNATURE	DATE
Project Manager		
ERDC/CERL Branch Chief		
Installation DPW POC		
IMA Region		
HQ IMA		6/15/05
HQ ACSIM		
HQ AMC		
Tri Service Facilities WIPT Chair		

This is a TriService Project. Funds have been requested for travel of Air Force and Navy representatives to participate in the evaluation of technology implementation.

ARMY FACILITIES

CORROSION PREVENTION AND CONTROL PROJECT PLAN
Remote Corrosion Sensors for Detection of Corrosion on Mission Essential Structures in Severely Corrosive Environments at Okinawa (RDT&E, FY06)

6. COORDINATION

ORGANIZATION	SIGNATURE	DATE
Project Manager		
ERDC/CERL Branch Chief		
Installation DPW POC		
IMA Region		
HQ IMA		
HQ ACSIM		15 Jun 05
HQ AMC		
Tri Service Facilities WIPT Chair		

This is a TriService Project. Funds have been requested for travel of Air Force and Navy representatives to participate in the evaluation of technology implementation.

ARMY FACILITIES

CORROSION PREVENTION AND CONTROL PROJECT PLAN
Remote Corrosion Sensors for Detection of Corrosion on Mission Essential Structures in Severely Corrosive Environments at Okinawa (RDT&E, FY06)

6. COORDINATION

ORGANIZATION	SIGNATURE	DATE
Project Manager	Ashok Kumar	6/13/05
ERDC/CERL Branch Chief	[signature]	6-15-05
Installation DPW POC	/s/	12 July 05
IMA Region	/s/	28 Sept 05
HQ IMA	/s/	15 June 05
HQ ACSIM	/s/	15 June 05
HQ AMC	[signature]	29 Sept
Tri Service Facilities WIPT Chair	/s/	15 June 05

This is a TriService Project. Funds have been requested for travel of Air Force and Navy representatives to participate in the evaluation of technology implementation.

ARMY FACILITIES

CORROSION PREVENTION AND CONTROL PROJECT PLAN
Remote Corrosion Sensors for Detection of Corrosion on Mission Essential Structures in Severely Corrosive Environments at Okinawa (RDT&E, FY06)

6. **COORDINATION**

ORGANIZATION	SIGNATURE	DATE
Project Manager	Ashok Kumar	6/13/05
ERDC/CERL Branch Chief	Mitchell Mason	6-13-05
Installation DPW POC		
IMA Region		
HQ IMA		
HQ ACSIM		
HQ AMC		
Tri Service Facilities WIPT Chair	Thomas Schade	6/15/05

This is a TriService Project. Funds have been requested for travel of Air Force and Navy representatives to participate in the evaluation of technology implementation.

6. APPENDICES

Appendix 1. Return On Investment (ROI) Calculations

Remote Corrosion Sensors for Detection of Corrosion on Mission Essential Structures in Severely Corrosive Environments at Okinawa (RDT&E, FY06)

Assumptions:

Alternative 1: The Okinawa C4ISR facility and dish antenna requires replacement 10 years from now, at a cost of $3.65M. The cost of the additional C4ISR Equipment which must be replaced is $16.5M for a total cost of $20.15M, as shown under *Baseline Costs*. Average annualized maintenance costs of the existing C4ISR facility is $350K, which drops to $75K after replacement of the facility, as shown under *Baseline Costs*, as remote sensors will be installed when the new facility is replaced.

The annual cost impact C4ISR downtime from year 1 to year 10 due to the loss of command, communications, control and computer equipment totals from $ 410K to $878K as shown under *New Systems Benefits/Savings.* The additional annual benefits/savings costs drop after the C4ISR Facility is replaced to $21K, but again increase linearly up to $383K, until the C4ISR Facility is replaced in Year 30.

Alternative 2: Installing remote sensing corrosion rate monitor in year 1 at a project cost of $900K is projected to extend the life of the C4ISR facility over the conventional maintenance schedule by another 30 years. Data from maintenance personnel indicate that early detection and subsequent preventive measures result in maintenance cost savings of 50%, (which means that the new system cost will be $175K) plus the annual cost of operating the sensors ($18K) for a total of $193,000 as shown under *New System Costs*. Under this alternative, the C4ISR Facility must be replaced in Year 30 at a cost of $20.15M.

Comparing the two alternatives, the potential return-on-investment for Alternative 2 is projected to be 14.

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Return on Investment Calculation

Investment Required			900,000
Return on Investment Ratio	14.03	Percent	1403%
Net Present Value of Costs and Benefits/Savings	5,017,229	17,646,044	12,628,815

A Future Year	B Baseline Costs	C Baseline Benefits/Savings	D New System Costs	E New System Benefits/Savings	F Present Value of Costs	G Present Value of Savings	H Total Present Value
1	350,000		193,000	410,000	180,378	710,296	529,918
2	350,000		193,000	451,000	168,566	699,593	531,027
3	350,000		193,000	496,100	157,546	690,671	533,126
4	350,000		193,000	545,710	147,240	683,337	536,097
5	350,000		193,000	600,281	137,609	677,550	539,941
6	350,000		193,000	660,309	128,596	673,169	544,573
7	350,000		193,000	726,340	120,181	670,237	550,056
8	350,000		193,000	798,974	112,326	668,703	556,377
9	350,000		193,000	878,871	104,973	668,383	563,410
10	20,150,000		193,000		98,102	10,242,245	10,144,143
11	75,000		193,000	21,000	91,694	45,610	-46,085
12	75,000		193,000	43,000	85,692	52,392	-33,300
13	75,000		193,000	63,000	80,095	57,270	-22,825
14	75,000		193,000	83,000	74,845	61,272	-13,573
15	75,000		193,000	103,000	69,943	64,507	-5,436
16	75,000		193,000	123,000	65,369	67,063	1,694
17	75,000		193,000	143,000	61,104	69,019	7,915
18	75,000		193,000	163,000	57,109	70,424	13,316
19	75,000		193,000	183,000	53,365	71,337	17,973
20	75,000		193,000	203,000	49,871	71,835	21,964
21	75,000		193,000	223,000	46,610	71,967	25,358
22	75,000		193,000	243,000	43,560	71,773	28,213
23	75,000		193,000	263,000	40,704	71,284	30,581
24	75,000		193,000	283,000	38,040	70,562	32,522
25	75,000		193,000	303,000	35,551	69,628	34,077
26	75,000		193,000	323,000	33,235	68,536	35,301
27	75,000		193,000	343,000	31,054	67,256	36,203
28	75,000		193,000	363,000	29,027	65,875	36,848
29	75,000		193,000	383,000	27,136	64,395	37,259
30	75,000		20,150,000		2,647,710	9,855	-2,637,855

ARMY FACILITIES
CORROSION PREVENTION AND CONTROL PROJECT PLAN
Remote Corrosion Sensors for Detection of Corrosion on Mission Essential Structures in Severely Corrosive Environments at Okinawa (RDT&E, FY06)

Appendix 2

DEPARTMENT OF THE ARMY
ASSISTANT CHIEF OF STAFF FOR INSTALLATION MANAGEMENT
600 ARMY PENTAGON
WASHINGTON DC 20310-0600

25 MAR 2005

DAIM-FD S: 15 Oct 2005

MEMORANDUM FOR DIRECTOR, INSTALLATION MANAGEMENT AGENCY, 2511 JEFFERSON DAVIS HIGHWAY, ARLINGTON VA 22202-3926

SUBJECT: FY 06 Army Corrosion Control Program

1. OSD has tentatively allocated a total of $15.0M in FY 06 matching funds for implementation of corrosion prevention and control projects for equipment and facilities. The enclosed list of Army projects, totaling $13.3M, will be presented for approval to OSD in April 05.

2. The Army programming target is not less than $10.0M of facility related projects in an effort to obtain a minimum of $5.0M of the OSD matching funds. To participate in OSD's funding augumentation, HQIMA will reserve $5.0M in FY06 OMA funds, to be released to ERDC-CERL upon confirmation by this office that OSD matching funds are available. Further instructions on the actual distribution of funds will follow at that time.

3. POC for this action is Mr. David N. Purcell, or (703) 601-0371, David.Purcell@hqda.army.mil.

4. Quality Facilities for Quality Soldiers!

FOR THE ASSISTANT CHIEF OF STAFF FOR INSTALLATION MANAGEMENT:

MARK A. LORING
Colonel, GS
Director, Facilities and Housing

Encl
as

CF:
DACSIM

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
August 2009	Final	

4. TITLE AND SUBTITLE
Implementation of Remote Corrosion-Monitoring Sensor for Mission-Essential Structures at Okinawa

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
Corrosion Prevention and Control

6. AUTHOR(S)
L.D. Stephenson, Ashok Kumar, John O'Day, Benjamin Caldwell, Kevin Kwan, and Bernard C. Laskowski

5d. PROJECT NUMBER
CPC FAR-04

5e. TASK NUMBER
MIPR6FCERB1020, MIPR6H6AG3CPC1

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Engineer Research and Development Center
Construction Engineering Research Laboratory
P.O. Box 9005
Champaign, IL 61826-9005

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC/CERL TR-09-30

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Installation Management Command
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2511 Jefferson Davis Hwy.
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10. SPONSOR/MONITOR'S ACRONYM(S)
IMCOM

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Additional Task Number is MIPR6HMBHDE097

14. ABSTRACT

This project demonstrated innovative remote sensors (LPR sensors) the size of postage stamps which can provide instantaneous corrosion rate data from under a coating. These sensors were installed beneath a coating on a mission critical metal structure roof in Okinawa, to detect the intrusion of moisture and predict the corrosion rates from the shifts in polarization resistance. With this real time data capability, early detection of the need for maintenance on the structure can be determined and corrections made, extending the service life of the structure and lowering life-cycle cost. This technology is applicable to metal roofs, water tanks, fences or any metal structures that early detection of corrosion is needed to extend the life of the structure, avoid costly early replacement or avoid complete failure of the structure. Standard coupon tests and electrical resistance (ER) probes provide corrosion rates at a lower cost than the LPR sensors but not instantaneous rates as does the LPR sensors. Standard coupon and ER probes were demonstrated on this project for comparison to LPR corrosion rate data and to obtain atmospheric corrosion rates in this highly corrosive environment.

15. SUBJECT TERMS
Okinawa, military installations, corrosion prevention and control, remote monitoring systems, corrosion sensors

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
Unclassified	Unclassified	Unclassified		248	