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Demonstration and Validation of Portable Electrochemical Impedance Spectroscopy Technology

Final Report on Project F11-AR08

Christopher Olaes, Richard G. Lampo, Lawrence Clark,
Susan A. Drozd, and Jeffrey P. Ryan

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Demonstration and Validation of Portable Electrochemical Impedance Spectroscopy Technology

Final Report on Project F11-AR08

Richard G. Lampo, Susan A. Drozdz, and Jeffrey P. Ryan

*Construction Engineering Research Laboratory
U.S. Army Engineer Research and Development Center
2902 Newmark Drive
Champaign, IL 61822*

Christopher Olaes and Lawrence Clark

*Mandaree Enterprise Corporation
812 Park Drive
Warner Robins, GA 31088*

Final report

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              Coating Sensors"

Abstract

The Department of Defense maintains many steel structures that are subject to corrosion. Coatings are a traditional first line of defense against corrosion, but a completely accurate assessment of coating condition cannot always be made by using only conventional visual inspection techniques because not all defects are visible. Alternatively, performing laboratory inspections can be difficult, time-consuming, costly, and may require testing specimens separately from the actual coated structure. This Office of the Secretary of Defense Corrosion Prevention and Control Program project sought to improve accuracy and lower costs (early detection of problems reduce future maintenance) by demonstrating and validating the capabilities of a portable electrochemical impedance spectroscopy (EIS) technology for evaluating coating health. A portable EIS system was demonstrated in a laboratory setting and at field locations on Fort Bragg, NC, and Fort Lewis, WA. The results showed the tested version of the portable EIS system has limited capabilities in comparison to traditional laboratory methods. Based on the results of the technology demonstration, the system needs further development before the anticipated benefits might be realized. Therefore, widespread implementation of the demonstrated system is not recommended at the current state, and the project's return on investment is considered to be zero.

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Preface

This study was conducted for the Office of the Secretary of Defense (OSD) under Corrosion Prevention and Control Program Project F11-AR08, “Portable Electrochemical Impedance Spectroscopy Coating Sensors.” The proponent was the U.S. Army Office of the Assistant Chief of Staff for Installation Management (OACSIM), and the stakeholder was the U.S. Army Installation Management Command (IMCOM). The technical monitors were Mr. Daniel J. Dunmire (OUSD(AT&L)), Mr. Ismael Melendez (IMPW-FM), and Ms. Valerie D. Hines (DAIM-ODF).

The work was performed by the Materials Branch of the Facilities Division (CEERD-CFM), U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL). A portion of the work was performed under contract with Mandaree Enterprise Corporation (MEC) of Warner Robins, GA. At the time of publication, Ms. Vicki L. Van Blaricum was Chief, CEERD-CFM; Mr. Donald K. Hicks was Chief, CEERD-CF; and Mr. Kurt Kinnevan, CEERD-CZT, was the Technical Director for Infrastructure for Combat Operations. The Deputy Director of ERDC-CERL was Dr. Kirankumar Topudurti, and the Director was Dr. Lance D. Hansen.

The following Fort Bragg and Fort Lewis personnel are gratefully acknowledged for their support and assistance in this project:

- Mr. Russell Castillio – Directorate of Public Works, Fort Bragg, NC
- Mr. Richard Golden – Directorate of Public Works, Fort Lewis, WA
- Mr. Kenneth Smith – Environmental Division Chief, Directorate of Public Works, Fort Lewis, WA

The authors also wish to acknowledge the assistance of Mr. Tanner J. Wood of the ERDC-CERL Paint Technology Center.

The outstanding contributions of Dr. John R. Scully, University of Virginia, are also acknowledged for conducting the laboratory evaluations.

The Commander of ERDC was COL Bryan S. Green, and the Director was Dr. David W. Pittman.

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

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1 Introduction

1.1 Problem statement

Corrosion of facilities and infrastructure costs the Department of Defense (DoD) an estimated \$3.0 billion annually. \$2.3 billion of which is associated with maintenance activities related to the effects of corrosion (Herzberg et al. 2014). Paint coatings are considered the traditional first line of defense against corrosion of steel (Shaw and Kelly 2006). However, coating quality degrades over time after continual exposure to solar ultraviolet (UV) radiation, water, environmental and manufactured sources of chlorides (i.e., salts), and corrosive chemicals. Also, even newly applied coatings may contain pinholes or other defects in the film. Poor coating condition is not always evident from visual inspection, and coating evaluation is complicated by subjectivity in the inspector's perceptions or interpretation of rating criteria. Thus a coating often may appear intact, providing no obvious signs that the steel substrate may be corroding immediately beneath.

Coating inspection quality and validity of results could be greatly improved through the application of a user-portable sensor device designed to read and record electrochemical data at the substrate surface and through a visibly intact coating. A tool with the ability to detect the onset and extent of corrosion that is occurring beneath the coating could extend the service life of steel structures owned or maintained by the DoD through improved maintenance schedules and allocation of resources. The use of such a tool could be optimized, through the development of new scheduling and sampling methods, to significantly reduce the amount of time needed for reliable field inspections. Also, the acquired sensor data could be integrated into a condition-based coating maintenance management system. A device capable of sensing corrosion activity beneath coats of paint would be useful on fixed facilities plus have potential usefulness for monitoring substrate corrosion on coated surface vehicles and aircraft.

Electrochemical impedance spectroscopy (EIS) is an established laboratory method used to determine and quantify the condition of a coating. A user-portable, EIS-based sensor device has the potential to greatly improve the efficiency of coating-condition field inspections and thus, it

could help to reduce the billions of dollars that DoD spends annually by facilitating timely maintenance to reduce corrosion-related infrastructure life-cycle costs.

1.2 Objective

This work's objective was to demonstrate and validate the use of a commercially available, EIS-based, portable, coating health monitor (CHM) for its effectiveness in providing accurate real-time data on the condition of a coating and any corrosion activity on the surface of the substrate.

1.3 Approach

To evaluate the ease of use and measurement capabilities of the portable EIS-based CHM, the research team performed both laboratory and field testing to evaluate the parameters of interest.

In the laboratory, the portable device was evaluated using coated metallic test panels. All of the panels were subjected to accelerated environmental exposure and then tested by using the portable EIS-based device and a conventional EIS-based laboratory potentiostat system. Data collected by the two systems were compared to evaluate the accuracy of the portable system compared to the conventional laboratory system.

Field testing of the portable CHM was performed on coated components of facilities located at Fort Bragg, North Carolina, and Fort Lewis, Washington. Facility test components were selected to include a variety of paint systems, substrates, and coating ages in order to detect changes in coating condition over time.

1.4 Metrics

The performance metrics for the EIS-based CHM were as follows:

- Accuracy of the tested CHM's measurements of coating impedance, as compared with the measurements made by a proven laboratory EIS instrument.
- Correlation of tested CHM's measurements with visual evaluations in both the laboratory and in the field that were performed according to ASTM D610 (2012) and ASTM D714 (2009).

- Comparison of measurements taken in the field over time to determine whether the tested device can detect coating changes or degradation over time.

2 Technical Investigation

2.1 Technology overview

EIS technology has long been used in the laboratory to investigate the performance of protective coatings applied to metallic substrates (Mansfeld and Tsai 1991; Scully and Hensley 1994). The primary measurement provided by the EIS technique is coating impedance. Advances in miniaturization of electronics components have led to the development of field-portable EIS instruments. The portable EIS-based CHM¹ instrument used in this demonstration was manufactured by ElectraWatch, Inc. of Charlottesville, Virginia. The device consists of a small potentiostat attached to two electrodes – a reference electrode and a working electrode (the working electrode being the coating substrate). A conductive grease is used to electrically couple the electrodes to the coated surface and to provide a continuous conductive path to the substrate. The CHM is held to ferrous structures with magnets and to nonferrous structures with suction cups (Figure 1). After performing a test cycle on a subject coating, the recorded data onboard the portable unit is downloaded to a computer, and software is used to generate an output graph and report.

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¹ Subsequently, “the CHM” is used in this report for brevity to refer to the portable EIS device and distinguish it from the laboratory-scale reference system.

Figure 1. Components of ElectraWatch EIS CHM are shown in three views. Views (a) and (b) show the CHM with magnetic attachment mechanisms, and view (c) shows the suction-cup attachment mechanism.

Figure 2 illustrates how EIS impedance measurements could be utilized for evaluating and monitoring coating health. It was envisioned that EIS measurements taken in the field on structures in service could be collected over time and used to predict coating life on the subject structures.

Figure 2. Example of how EIS impedance measurements could be utilized to evaluate and monitor coating health.

Impedance [Z], Ohms/cm ²	Coating Condition
$> 10^8$	Excellent
$10^7 - 10^8$	Good
$10^5 - 10^7$	Moderate
$< 10^5$	Poor

(Note: Figure continues with descriptions of the four conditions on the next page.)

Excellent	Coating system is providing excellent corrosion prevention as designed. No action required.
Good	Coating system is beginning to degrade; however corrosion prevention is adequate. Begin to closely monitor for continued degradation.
Moderate	Coating system is expected to be showing visual signs of degradation. Corrosion protection may become limited in subsequent years. Consider scheduling an overcoat before additional degradation.
Poor	Coating system may no longer be providing acceptable corrosion prevention. Remove and replacement should be scheduled.

2.2 Laboratory evaluation

A series of tests was performed in the laboratory to compare the coating condition measurements made by the CHM to a calibrated laboratory EIS system. The laboratory EIS system used in this project was the Gamry Reference 600.²

A total of 104 coated test panels were prepared for evaluation, as described below. Five sets of 12 sandblasted steel test panels were prepared using five different coating systems commonly used in corrosive environments. Three of the five coating systems were also used to prepare another three sets of 12 panels where the surface of the steel panels were contaminated to create artificial coating defects. Details of the different coating systems and surface contaminants are shown in Table 1. (Panels Fo–F11 are the same as panels Co–C11 except for the surface contamination; panels Go–G11 are the same as panels Ao–A11 except for the surface contamination; and panels Ho–H11 are the same as panels Bo–B11 except for the surface contamination.) Galvalume-coated steel roofing panels with a Polyvinylidene Fluoride (PVDF) top coating, as installed on the Fort Lewis Environmental Education and Conference Center (E2C2; Figure 3) but not exposed to the weather, were cut into eight 3 x 6 in. test panels for testing (also shown in Table 1).

² Gamry Instruments of Warrington, PA; website www.gamry.com.

Figure 3. Standing-seam metal roof on Fort Lewis E2C2 building, shown during reclamation and rehabilitation project (Lampo, Napier, and Schneider 2009).

Baseline measurements using the CHM and the laboratory EIS system were performed by Dr. John Scully at the University of Virginia, before any of the test panels were exposed to accelerated weathering and corrosive conditions. The test panels were then subjected to alternating exposures of salt fog and UV radiation in accordance with ASTM standard practices B117 (2016) and D5894 (2016), respectively. A test cycle was defined as two weeks in the UV cabinet and two weeks in the salt spray apparatus.

Two specimens from each set of panels were removed from the exposure chambers after 2 test cycles, 4 test cycles, 8 test cycles, and 10 test cycles,. The panels were first evaluated visually according to ASTM D610, Standard Practice for Evaluating Degree of Rusting on Painted Steel Surfaces; and ASTM D714, Standard Test Method for Evaluating Degree of Blistering of Paints. One of the two specimens was then subjected to EIS measurements using the portable CHM and the other specimen was subjected to the laboratory-based EIS system. Details of the laboratory testing procedures are presented in Appendix A.

Table 1. Coating systems applied to laboratory test panels.

Substrate	EIS Matrix																
	Coating Systems				Panel #	Avg. Coating Thickness (mils)											
						Primer				Topcoat				Total System			
	Primer	Topcoat	Contaminate	Total Panels tested		High	Low	Mean	Sdev	High	Low	Mean	Sdev	High	Low	Mean	Sdev
QLab CRS SAE 1008/1010 cold rolled, mild steel	MPI 23 - S.W. Kem Bond HS	MPI 9 - S.W. Seaguard 1000 Marine Enamel, White		12	A0-A11	3.09	2.11	2.65	0.32	2.13	1.16	1.66	0.17	5.22	3.27	4.31	0.49
QLab CRS SAE 1008/1010 cold rolled, mild steel	MPI 134 - S.W. DTM Acrylic Primer/Finish	MPI 11 - S.W. A100 Exterior Latex Gloss		12	B0-B11	1.78	0.99	1.48	0.19	1.74	1.39	1.41	0.12	3.52	2.38	2.89	0.31
QLab CRS SAE 1008/1010 cold rolled, mild steel	S.W. MIL-DTL-24441/29B F-150 Type 4	S.W. MIL-DTL-24441/31B F-152 Type 4		12	C0-C11	2.91	1.69	2.33	0.37	4.37	2.68	3.73	0.51	7.28	4.37	6.06	0.88
QLab CRS SAE 1008/1010 cold rolled, mild steel	SSPC Paint 41 - S.W. Corothane I Ironox B	SSPC Paint 38 - Corothane I HS White		12	D0-D11	2.65	1.49	1.99	0.29	4.6	2.07	3.65	0.73	7.25	3.56	5.64	1.02
QLab CRS SAE 1008/1010 cold rolled, mild steel	S.W. MIL-DTL-24441/19B F-159 Type 3	S.W. MIL-DTL-24441/31B F-152 Type 4		12	E0-E11	3.45	1.60	2.58	0.50	3.6	2.58	3.15	0.27	7.05	4.18	5.73	0.77
QLab CRS SAE 1008/1010 cold rolled, mild steel	S.W. MIL-DTL-24441/29B F-150 Type 4	S.W. MIL-DTL-24441/31B F-152 Type 4	50 micro grams/cm^2 Cl	12	F0-F11	3.56	1.60	2.72	0.58	4.28	2.7	3.56	0.6	7.84	4.3	6.28	1.18
QLab CRS SAE 1008/1010 cold rolled, mild steel	MPI 23 - S.W. Kem Bond HS	MPI 9 - S.W. Seaguard 1000 Marine Enamel, White	Flash Rust from tap water	12	G0-G11	3.76	1.83	2.81	0.42	3.42	1.72	2.13	0.33	7.18	3.55	4.94	0.75
QLab CRS SAE 1008/1010 cold rolled, mild steel	MPI 134 - S.W. DTM Acrylic Primer/Finish	MPI 11 - S.W. A100 Exterior Latex Gloss	Fine Soil	12	H0-H11	2.08	1.25	1.70	0.26	1.5	0.84	1.92	0.14	3.58	2.09	2.78	0.4
Galvalume, a 24 gage, carbon steel sheet coated with an aluminum-zinc alloy	aluminum-zinc alloy	Kynar 500, polyvinylidene fluoride (PVDF)		8	I0-I7	****	****	****	****	****	****	****	****	2.61	1.53	2.18	0.31

2.3 Field work

Most of the coatings used in the field testing in this project were relatively newly applied, with coating applications taking place as part of previous CPC Program projects (project numbers and published report numbers shown below). The following three coating test locations occurred at Fort Bragg:

- Central Vehicle Wash Facility (CVWF) ductile iron piping sections were treated with a self-healing coating system in 2007 (CPC Project F06, FAR-02; ERDC/CERL TR-09-31 – Kumar et al. 2009).
- Steel fuel oil-storage tank (200,000 gallons) at the 82nd Heating Plant on Campobello Street, which was treated in 2008 with an innovative primer coating containing carbon nanotubes in an epoxy/polyurethane system (CPC Project F07-AR19; ERDC/CERL TR-11-42 – Drozd et al. 2011).
- “Old Division” water tank No. C2714 (at intersection of Gruber Road and Biazza Street) was coated with a conventional epoxy system that was 15+ years old, and “New Division” water tank No. C7024 (at intersection of Gruber Road and All American Way) was coated in 2008 by using a thermoplastic spray process (CPC Project F07-AR10; ERDC/CERL TR-17-30 – Stephenson et al. 2017).

Two coating test locations were used at Fort Lewis, as listed below:

- Davis Hill water tank (located near the intersection of Texas Avenue and North 8th Street) is a steel potable water tank, which was coated on the exterior in 2010 using an epoxy nanocoating system with an inherently conductive polymer primer (CPC Project F09-AR19; publication pending).
- E2C2 standing seam metal roof (intersection of 7th Street and DuPont-Steilacoom Road on north side of installation), which was installed new in 2007 (CPC Project FY06, FAR21; ERDC/CERL TR-09-25 – Lampo, Napier, and Schneider 2009).

Photos of the field test structures are shown in Appendix B.

Before each CHM measurement, visual assessments of the coated areas were conducted and rated according to ASTM D610 and ASTM D714 by author Chris Olaes, a certified NACE engineer employed by the contractor. Before testing began, a resistor with a known value was used to conduct a

control measurement to ensure that the CHM was operating correctly. Before attaching the system to a test surface, an ammonia-based surface cleaner was used to remove dirt and debris from the coating surface. To ensure a continuous conductive path, silver conductive grease was applied to the CHM copper reference electrode and to the coating surface where the electrode would make contact with the coating surface. Before placing the CHM electrode onto the coating surface, the surrounding surface and conductively greased area were wetted with water from a spray bottle. The CHM was then held to the steel test surface by engaging two magnets. Suction cups were also provided to mount the instrument to flat, nonmagnetic substrates. An electrical grounding location on the coated structure was selected, and a 1 x 1 in. section of the coating was removed using a rotary tool and sanding attachment. The exposed bare metal surface was covered with a piece of aluminum foil tape, to which the CHM system electrical ground (that is, the coating substrate which is the “working electrode”) wire was attached via an alligator clip.

It was determined that the CHM required the surface to be thoroughly wetted in order to obtain a measurement. If the surrounding surface dried before completing the measurement, the surface was rewetted without removal of the CHM system. Depending on the type and integrity of the coating being analyzed, a measurement set took between 4 and 40 minutes to collect at each site.

2.4 Performance monitoring

Measurements were collected using the CHM system at Fort Bragg and Fort Lewis at approximately 6-month intervals during the 24-month test period. Visual assessments were also performed at those same times.

Due to site inaccessibility, the measurements to be taken at the 6-month interval could not be collected at the Davis Hill Water Tower test site at Fort Lewis.

3 Discussion

3.1 Results

3.1.1 Laboratory testing results

Comparison of the CHM results to the laboratory EIS system can be divided into three cases. This division assesses the ability of the CHM to identify the electrical properties of the coating systems when the impedance (1) remains high (indicates a good coating), (2) drops slightly over the various cycles (indicates a fair coating), or (3) drops considerably (indicates a poor coating). The three cases are described as follows (note that more details about coating groups and laboratory testing are given in Appendix A):

1. A very **good coating** with high impedance over the duration of the accelerated weathering cycles, as exemplified by coating C (refer to “Panel” column for Co-C9 results in Table 1 and see Figure 4). The impedance remained high, and the ASTM ratings showed less-pronounced decreases with increasing number of exposure cycles. The CHM system could not measure the impedance other than the instrument’s upper limit of 5×10^8 ohms.
2. A **fair coating**, exemplified by coating E (panels E0-E9 results in Table 1 and see Figure 5). The CHM and laboratory EIS system data were different where the CHM remained unchanged at 5×10^8 ohms, while the EIS system impedance changed with time. The ASTM ratings decreased monotonically with time.
3. Two very **poor coatings**, exemplified by coatings A and B (see panels A0-A9 and B0-B9 results in Table 1 plus Figure 6 and Figure 7, respectively). For coating A, the EIS resistance measurement and ASTM rating began to drop after 16 weeks (4 cycles) of exposure. The CHM measurement remained at 5×10^8 ohms and indicated a lower value only when the impedance dropped below about 5×10^7 ohms. Coating B behaved similarly (Figure 7). The CHM began to indicate the impedance when it dropped below $\sim 10^7$ ohms.

Most of the coating systems, except A and B, exhibited impedance values near 5×10^8 ohms or between 10^9 and 10^7 ohms. However, the good-to-fair coatings also exhibited impedance in this same range. This result means

the CHM was unable to indicate the true impedance of these coating systems. This result also means that only the very poor coatings—those with impedance values below 10^7 – 10^6 ohms—could be measured with any accuracy by the CHM.

The published impedance measurement limit of the CHM was 5×10^8 ohms, but these test results suggest that the upper limit of the instrument was actually 1×10^7 ohms. Again, note that detailed results of the laboratory panel tests are presented in Appendix A, with photos of the test panels shown in Appendix C.

Figure 4. Results for a coating C panel are shown as follows: (a) comparison of CHM and Gamry Reference 600, (b) appearance of panel C10 at 40 weeks (10 cycles) exposure, and (c) ASTM ratings versus time.

Figure 5. Results for a coating E panel are shown as follows: (a) comparison of CHM and Gamry Reference 600, (b) appearance of panel E10 at 40 weeks (10 cycles) exposure, and (c) ASTM ratings versus time.

Figure 6. Results for a coating A panel are shown as follows: (a) comparison of CHM and Gamry Reference 600, (b) appearance of panel A10 at 40 weeks (10 cycles) exposure, and (c) ASTM ratings versus time.

Figure 7. Results for a coating B panel are shown as follows: (a) comparison of CHM and Gamry Reference 600, (b) appearance of panel B10 at 16 weeks (4 cycles) exposure, and (c) ASTM ratings versus time.

3.1.2 Field testing results

The results from the ASTM D610 and ASTM D714 visual assessments are listed in Table 2–Table 4.

Table 2. ASTM D610 and ASTM D714 inspection results from the Old Division water tower and the New Division water tower at Fort Bragg.

Test Site	Location	Month	ASTM D610		ASTM D714	
			0-10	S,G,P	0-10	D,MD,M,F
Old Division Water Tower	1	0	10	none	10	n/a
		6	10	none	10	n/a
		12	10	none	10	n/a
		18	10	none	10	n/a
	2	0	10	none	10	n/a
		6	10	none	10	n/a
		12	10	none	10	n/a
		18	10	none	10	n/a
	3	0	10	none	10	n/a
		6	10	none	10	n/a
		12	10	none	10	n/a
		18	10	none	10	n/a
	4	0	10	none	10	n/a
		6	10	none	10	n/a
		12	10	none	10	n/a
		18	10	none	10	n/a
New Division Water Tower	1	0	10	none	10	n/a
		6	10	none	10	n/a
		12	10	none	10	n/a
		18	10	none	10	n/a
	2	0	10	none	10	n/a
		6	10	none	10	n/a
		12	10	none	10	n/a
		18	10	none	10	n/a
	3	0	10	none	10	n/a
		6	10	none	10	n/a
		12	10	none	10	n/a
		18	10	none	10	n/a
	4	0	10	none	10	n/a
		6	10	none	10	n/a
		12	10	none	10	n/a
		18	10	none	10	n/a

Table 3. ASTM D610 and ASTM D714 results from the central vehicle wash facility and the 82nd heating plant fuel tank at Fort Bragg.

Test Site	Location	Month	ASTM D610		ASTM D714	
			0-10	S,G,P	0-10	D,MD,M,F
Central Wash Facility	1	0	10	none	10	n/a
		6	10	none	10	n/a
		12	10	none	10	n/a
		18	10	none	10	n/a
	2	0	10	none	10	n/a
		6	10	none	10	n/a
		12	10	none	10	n/a
		18	10	none	10	n/a
	3	0	10	none	10	n/a
		6	10	none	10	n/a
		12	10	none	10	n/a
		18	10	none	10	n/a
	4	0	10	none	10	n/a
		6	10	none	10	n/a
		12	10	none	10	n/a
		18	10	none	10	n/a
82 nd Heating Plant Fuel Tank	1	0	10	none	10	n/a
		6	10	none	10	n/a
		12	10	none	10	n/a
		18	10	none	10	n/a
	2	0	10	none	10	n/a
		6	10	none	10	n/a
		12	10	none	10	n/a
		18	10	none	10	n/a
	3	0	10	none	10	n/a
		6	10	none	10	n/a
		12	10	none	10	n/a
		18	10	none	10	n/a
	4	0	10	none	10	n/a
		6	10	none	10	n/a
		12	10	none	10	n/a
		18	10	none	10	n/a

Table 4. ASTM D610 and ASTM D714 results from the Davis Hill water tower and the E2C2 building roof at Fort Lewis.

Test Site	Location	Month	ASTM D610		ASTM D714	
			0-10	S,G,P	0-10	D,MD,M,F
Davis Hill Water Tower	1	0	10	none	10	n/a
		6	10	none	10	n/a
		12	10	none	10	n/a
		18	10	none	10	n/a
	2	0	10	none	10	n/a
		6	10	none	10	n/a
		12	10	none	10	n/a
		18	10	none	10	n/a
	3	0	10	none	10	n/a
		6	10	none	10	n/a
		12	10	none	10	n/a
		18	10	none	10	n/a
	4	0	10	none	10	n/a
		6	10	none	10	n/a
		12	10	none	10	n/a
		18	10	none	10	n/a
E2C2 Building Roof	1	0	10	none	10	n/a
		6	10	none	10	n/a
		12	10	none	10	n/a
		18	10	none	10	n/a
	2	0	10	none	10	n/a
		6	10	none	10	n/a
		12	10	none	10	n/a
		18	10	none	10	n/a
	3	0	10	none	10	n/a
		6	10	none	10	n/a
		12	10	none	10	n/a
		18	10	none	10	n/a
	4	0	10	none	10	n/a
		6	10	none	10	n/a
		12	10	none	10	n/a
		18	10	none	10	n/a

There were no signs of rust or blistering of the coatings at any of the test locations. Additionally, there was no change in the visual assessment results over the duration of this project. However, the Old Division water tower coating showed signs of oxidation, accidental damage, and coating

failures to varying degrees of severity at nearby locations. Areas that experienced coating failures were rusted; however, the locations at which the CHM was used to measure impedance were not taken directly at these corroded areas.

It was expected that EIS measurements taken with the CHM on coating systems over different metallic substrates would produce different ranges of impedance data. With the exception of the Old Division water tower at Fort Bragg, the coatings on steel substructures and the aluminum alloy coated steel roof indicated impedance values in the 10^7 – 10^8 ohms range and above the accuracy threshold determined in the laboratory test comparison of the CHM.

The EIS impedance values from the Old Division tower were significantly lower by a factor of 10 – 10^2 . Although the coating on the vehicle wash station at Fort Bragg was in good condition, it was constructed with ductile iron and the coating impedance was within the measurement range of the CHM. Figure 8 depicts a slight downward trend of the coating impedance at location 3 of the CVWF.

Figure 8. Central vehicle wash facility, Fort Bragg, test location 3, impedance results from the CHM in ohms/cm².

	Frequency	Z 0.2 Hz	Z 0.5 Hz	Z 0.9 Hz
Month	0	1.92E+06	1.66E+06	1.85E+06
	6	6.79E+05	6.49E+05	5.59E+05
	12	1.27E+06	1.13E+06	1.09E+06
	18	4.76E+05	3.32E+05	2.82E+05

Specific results from the other test locations at each site are charted in Appendix D, in a format like Figure 8.

In summary, field testing results show that the version of the CHM used in this study cannot measure the impedance of good-quality coatings on steel or aluminum substrates.

3.2 Lessons learned

As indicated above, the authors learned that the CHM in its tested configuration is not capable of accurately measuring impedance values when they are above 5×10^7 ohms. In this situation, the system indicates a default value of about 5×10^8 ohms, which is not the true impedance of the system.

4 Economic Analysis

4.1 Costs and assumptions

Total project costs were \$584,920, as shown in Table 5. A rough breakdown of project expenses is presented in Table 6. Note that in the original Project Management Plan (PMP) for Project F11-AR08, the project total was \$500,000. Mainly due to subsequently higher in-house costs, the project's scope was increased to the final project total of \$584,920.

Table 5. Breakdown of total project costs.

Description	Amount, \$K
Labor	300
Contracts	229.9
Travel	30
Reporting	15
Air Force and Navy participation	10
Total	584.9

A breakdown of the field demonstration contract portion of the above costs for this CPC project are shown in Table 6.

Table 6. Project field demonstration costs.

Item	Description	Amount, \$K
1	Labor for project management and execution	107.9
2	Travel for project management and execution	26.8
3	Cost for equipment, shipping, training	18.8
4	Subcontracting (laboratory work and peer review)	76.4
	Total	229.9

4.2 Example projected economic benefit (using Davis Hill Water Tower, Fort Lewis, as an example)

The cost of labor for this economic study example was calculated by using a maintenance/data analyst labor rate of \$73.52 per hour, an amount supplied by the contractor. It was conservatively assumed that each reading would take the full 40 minutes to collect under the current design of the system and an additional 20 minutes to conduct the setup of the instrument and surface preparations at each tested location. When collecting

four measurements at each site similar to the field testing completed in this project, it was calculated that one site would require four hours of labor, totaling \$294.08. In addition, according to the contractor, the investment cost of the portable EIS equipment, including training, was \$7,245.

Collecting coating health data provides quantitative measures and trend analyses for determining replacement or repair requirements and schedules that a visual inspection would otherwise not present. Although chalking and other signs of wear can be aesthetically displeasing, often times the coating system continues to provide corrosion protection. In the case of the Davis Hill water tower, the coating system was five years into its life cycle and beginning to show signs of oxidation; however, the EIS measurement provided quantitative justification that the coating system was still intact and providing corrosion protection to the structure.

Therefore, it is assumed that without the EIS data, the Davis Hill water tower coating system would be scheduled for removal and replacement within the next 10 years due to an oxidized appearance; however, EIS data provided sufficient justification to keep the coating system untouched or to conduct touch-up and overcoat of the structure and extend the coating system's function to its designed service life of 30 years. The material cost of coating the Davis Hill water tower in 2009 was \$139,570. The total labor cost (including the blasting operation and equipment) was \$922,478. The approximate touch-up and overcoat labor and equipment costs would be \$333,928 if executed instead of the strip and recoat (overcoat) at the 15-year life cycle mark. The overcoat assumes the use of MIL-D-24441 formula 152 primer and MIL-STD-85285 topcoat for a total cost of \$82,250 in materials.

The total initial investment of the CHM system by Fort Lewis would be \$7,245 (includes training) per the project's contractor. Although each coating system may require different measurement times for data collection, this economic benefit was calculated based on obtaining a set of EIS measurements for \$294 per year, as explained above. The total savings of applying an overcoat versus a complete strip and recoat was \$645,870 each time for year 10 and year 25. The original economic benefit (a return on investment [ROI] in this case), based on the OMB circular A-94 (OMB 1992), was calculated to be 61.2 (shown in Table 7). This benefit calculation represents the *potential* value of implementing the CHM and a condition-based maintenance system on structural coatings. Other scenarios on less

complicated structures may impact the realized benefit. Also consider that the above example involved a case where the coating system was visually indicating deterioration and the need for recoating but, in fact, the coating was still providing corrosion protection according to the CHM measurements. If the coating system appearance indicated still-acceptable protection after 15 years of service, then recoating would not be scheduled based on appearance, and yearly measurements using the CHM would not be productive.

Table 7. Investment benefits calculation.

Investment Required				7,245			
Return on Investment Ratio				61.23	Percent	6123%	
Net Present Value of Costs and Benefits/Savings				3,648	447,265	443,617	
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			294		275		-275
2			294		257		-257
3			294		240		-240
4			294		224		-224
5			294		210		-210
6			294		196		-196
7			294		183		-183
8			294		171		-171
9			294		160		-160
10			294	645,870	149	328,296	328,146
11			294		140		-140
12			294		131		-131
13			294		122		-122
14			294		114		-114
15			294		107		-107
16			294		100		-100
17			294		93		-93
18			294		87		-87
19			294		81		-81
20			294		76		-76
21			294		71		-71
22			294		66		-66
23			294		62		-62
24			294		58		-58
25			294	645,870	54	118,969	118,915
26			294		51		-51
27			294		47		-47
28			294		44		-44
29			294		41		-41
30			294		39		-39

4.3 Projected return on investment on overall project

While the ElectraWatch portable CHM system shows promise, the instrument, as demonstrated in this project, is not recommended for use across the Services for coating assessment and condition based maintenance

management systems (See Conclusions and Recommendations in Chapter 5). The estimated ROI in the original PMP assumed the following:

- The Army-wide budget for annual maintenance painting of installation infrastructure is \$6,000,000.
- The cost of corrosion inspection and maintenance is reduced by 10% annually, due to early detection of coating failures.

Given a total planned project execution cost of \$500,000, the originally calculated ROI was 14.9. (Note again that due to an increase in the funding requirement, the actual final total execution cost was \$584,920.)

Because implementation of the portable CHM system is not recommended in the tested configuration, the assumed benefits cannot be provided, and the actual ROI for the overall project is zero.

5 Conclusions and Recommendations

5.1 Conclusions

The CHM in its current configuration is not capable of accurately measuring impedance values when they are above 5×10^7 ohms. In this situation, the coating system indicates a default value of about 5×10^8 ohms when measured by the CHM, which is not the true impedance of the coating system.

The CHM could only measure the impedance once it dropped to a notably lower value. Thus, the tested CHM system can measure the impedance only of very bad coatings but not of extremely good coatings (where impedance is too high for the CHM to take proper measurements).

5.2 Recommendations

5.2.1 Applicability

A properly functioning CHM would be applicable to any aboveground coated metallic structure. However, the state of technology at the time this project was conducted was not sufficiently advanced to recommend it for application by DoD users.

5.2.2 Implementation

The ElectraWatch field-portable CHM system shows promise but in the configuration and state of technology development demonstrated at the time of this project, the instrument is not recommended for use across the DoD for coating assessment and condition-based maintenance management systems.

5.2.3 Future work

Several elements of the CHM design would need to be addressed before it could be evaluated again for DoD implementation. Specifically, the impedance measurement limit should be increased to a minimum of 10^9 ohms. Additionally, the test frequency operating range should be broadened so that it is similar to the laboratory-based, full-spectrum EIS systems. These improved design features would provide a higher level of reliability, accuracy, and integrity. However, those added capabilities could affect technology cost, so a new economic analysis would be required. Further

discussion and suggestions regarding recommendations for improvements to the instrument can be found in Appendix E.

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Appendix A: Details of Laboratory Testing

A series of tests were conducted using both the CHM and a Gamry Reference 600 laboratory EIS system for measuring the degradation of coatings. Coated test panels were prepared as per the explanation and tally statements that follow. Five different coating systems were applied to clean, blasted 3 x 6 in. steel panels. Three of the five coating systems were also applied to steel panels that were purposely surface contaminated to create artificial coating defects. Twelve panels were fabricated for each of the eight coating system variations. Retained metal roofing panels, the same as installed on the E2C2 building at Fort Lewis but never exposed to the weather, were cut into 3-inch by 6-inch sample test panels. This accounting results in a total of 104 test panels (as listed in Table A1). Measurements using both of the EIS instruments (laboratory and portable) were performed on the coupons to create a baseline set of data before any coupons were exposed to accelerated weathering and corrosive conditions. The test panels were then exposed to alternating exposures of salt (fog) and ultraviolet (UV) radiation in accordance with ASTM Standards B117 (2016) and D5894 (2016), respectively. A test cycle was defined as two weeks in the UV cabinet and two weeks in the salt spray apparatus. After four cycles (16 weeks total), two specimen pieces were removed. One of the removed specimens was subjected to EIS measurements using the portable CHM and the other specimen was measured by the laboratory-based EIS system. This process was repeated again after 10 cycles. Visual assessments of the coated specimens were conducted and rated before each EIS measurement.

The alternating exposures of salt (fog) and UV radiation were conducted per a modified ASTM D5894, Standard Practice for Cyclic Salt Fog/UV Exposure for Painted Metal (Alternating Exposures in a Fog/Dry Cabinet and a UV/Condensation Cabinet) procedure to artificially accelerate the degradation of the coated test specimens. For the purposes of this project, ASTM D5894 was modified to test the samples per ASTM B117, Standard Practice for Operating Salt Spray (Fog) Apparatus, instead of ASTM G85, Standard Practice for Modified Salt Spray (Fog) Testing.

Table A1. Coating systems applied to laboratory test panels.

Substrate	EIS Matrix																
	Coating Systems				Panel #	Avg. Coating Thickness (mils)											
						Primer				Topcoat				Total System			
	Primer	Topcoat	Contaminate	Total Panels tested		High	Low	Mean	Sdev	High	Low	Mean	Sdev	High	Low	Mean	Sdev
QLab CRS SAE 1008/1010 cold rolled, mild steel	MPI 23 - S.W. Kem Bond HS	MPI 9 - S.W. Seaguard 1000 Marine Enamel, White		12	A0-A11	3.09	2.11	2.65	0.32	2.13	1.16	1.66	0.17	5.22	3.27	4.31	0.49
QLab CRS SAE 1008/1010 cold rolled, mild steel	MPI 134 - S.W. DTM Acrylic Primer/Finish	MPI 11 - S.W. A100 Exterior Latex Gloss		12	B0-B11	1.78	0.99	1.48	0.19	1.74	1.39	1.41	0.12	3.52	2.38	2.89	0.31
QLab CRS SAE 1008/1010 cold rolled, mild steel	S.W. MIL-DTL-24441/29B F-150 Type 4	S.W. MIL-DTL-24441/31B F-152 Type 4		12	C0-C11	2.91	1.69	2.33	0.37	4.37	2.68	3.73	0.51	7.28	4.37	6.06	0.88
QLab CRS SAE 1008/1010 cold rolled, mild steel	SSPC Paint 41 - S.W. Corothane I Ironox B	SSPC Paint 38 - Corothane I HS White		12	D0-D11	2.65	1.49	1.99	0.29	4.6	2.07	3.65	0.73	7.25	3.56	5.64	1.02
QLab CRS SAE 1008/1010 cold rolled, mild steel	S.W. MIL-DTL-24441/19B F-159 Type 3	S.W. MIL-DTL-24441/31B F-152 Type 4		12	E0-E11	3.45	1.60	2.58	0.50	3.6	2.58	3.15	0.27	7.05	4.18	5.73	0.77
QLab CRS SAE 1008/1010 cold rolled, mild steel	S.W. MIL-DTL-24441/29B F-150 Type 4	S.W. MIL-DTL-24441/31B F-152 Type 4	50 micro grams/cm^2 Cl	12	F0-F11	3.56	1.60	2.72	0.58	4.28	2.7	3.56	0.6	7.84	4.3	6.28	1.18
QLab CRS SAE 1008/1010 cold rolled, mild steel	MPI 23 - S.W. Kem Bond HS	MPI 9 - S.W. Seaguard 1000 Marine Enamel, White	Flash Rust from tap water	12	G0-G11	3.76	1.83	2.81	0.42	3.42	1.72	2.13	0.33	7.18	3.55	4.94	0.75
QLab CRS SAE 1008/1010 cold rolled, mild steel	MPI 134 - S.W. DTM Acrylic Primer/Finish	MPI 11 - S.W. A100 Exterior Latex Gloss	Fine Soil	12	H0-H11	2.08	1.25	1.70	0.26	1.5	0.84	1.92	0.14	3.58	2.09	2.78	0.4
Galvalume, a 24 gage, carbon steel sheet coated with an aluminum-zinc alloy	aluminum-zinc alloy	Kynar 500, polyvinylidene fluoride (PVDF)		8	I0-I7	****	****	****	****	****	****	****	****	2.61	1.53	2.18	0.31

The schedule of testing is listed in Table A2. Table A3 indicates the coated panel numbering scheme. In Table A3, an R in the panel number indicates the scheduled removal and test scheme for EIS tests. The coupons marked “all R” indicate the panel was removed and placed back in exposure—thus used continuously. EIS measurements were conducted using the Gamry 600 system (100 mV amplitude) and the CHM system. In both cases, the same copper plate was used as the counter electrode (CE). The footprint of the plate is shown in Figures A1 and A2. The open circuit potential (OCP) data are shown in Figure A1. EIS measurements were conducted over a frequency range of 10^5 to 10^{-2} Hz with the Gamry system, and at 0.2, 0.5, and 0.9 Hz with the CHM system. Six points per decade of EIS data were acquired except for the pure resistor dummy cells. A popular graphical method of presenting EIS data is called the Bode plot in which the logarithm of the measured impedance and logarithm of the phase angle are plotted on the y-axis, and the logarithm of the test frequency is plotted on the x-axis. At low frequencies, very high impedance values (e.g., on the order of 10^8 ohms or higher) indicate good protection by coatings; in contrast, impedance values on the order of 10^5 ohms indicate corrosion and poor protection. The EIS spectra were similar (Figure A2), validating the use of the copper CE in the CHM instrument.

Visual assessments of the coated specimens were conducted in the field and in the laboratory, and those assessments were rated before each EIS measurement per ASTM D610, Standard Practice for Evaluating Degree of Rusting on Painted Steel Surfaces, and ASTM D714, Standard Test Method for Evaluating Degree of Blistering of Paints. The laboratory panels were scanned in color and the software tool, Image JTM, was used to digitally record rust areas (Figure A3). The method calibrates well across all rust types – whether S, G or P. The Image J software was used to analyze the color differentials of rust on each sample. The software produces a gray-scale image and quantifies the amount of color change on the surface of the sample. This method provides a quantity of rust, but it could not distinguish rust bleed over a coating from actual coating damage.

Table A2. Roofing panel test protocol with original planned dates shown.
4 cycles = R1, while 10 cycles = R2.

Schedule		DATE	Roofing Panel from E2C2 (6 panels total required)
cycles	weeks		(SOW Task 3 Para 2)
0	0	3/13/2013	Measure EIS on 1 panel w/ traditional instrument and on 1 panel w/ portable system
2	8		
4	16	7/3/2013	Remove 2 panels from cabinet exposure Conduct visual assessment via ASTM D610 and D714 of each panel Measure EIS on 1 panel w/ traditional instrument and on 1 panel w/ portable system
6	24		
8 10	32 40	10/23/2013 12/16/2013	Remove 2 panels from cabinet exposure Conduct visual assessment via ASTM D610 and D714 of each panel Measure EIS on 1 panel w/ traditional instrument and on 1 panel w/ portable system

Table A3. Coated panel identification key. The coated panels were labeled as indicated. R indicates the test cycles as shown in Tables 2 and 5. Panels labeled "all R" were tested and re-exposed in the test chambers; and sequentially removed and basically the same areas were retested. Therefore panels I6 and I7 were tested at all removals, while A10 through H10 were tested at all removal times; these panels are labeled "continuous" in the results section (section 3.1).

		Panel ID											
		Batch #1										Batch #2	
	Stackup	0	1	2	3	4	5	6	7	8	9	10	11
Task 3.3	A	T = 0	T = 0	R1	R1	R2	R2	R3	R3	R4	R4	all R	T = 0
	B	T = 0	T = 0	R1	R1	R2	R2	R2.5*	R2.5*	R2.5*	R2.5*	all R	T = 0
	C	T = 0	T = 0	R1	R1	R2	R2	R3	R3	R4	R4	all R	T = 0
	D	T = 0	T = 0	R1	R1	R2	R2	R3	R3	R4	R4	all R	T = 0
	E	T = 0	T = 0	R1	R1	R2	R2	R3	R3	R4	R4	all R	T = 0
	F	T = 0	T = 0	R1	R1	R2	R2	R3	R3	R4	R4	all R	T = 0
	G	T = 0	T = 0	R1	R1	R2	R2	R3	R3	R4	R4	all R	T = 0
	H	T = 0	T = 0	R1	R1	R2	R2	R2.5*	R2.5*	R2.5*	R2.5*	all R	T = 0
Task 3.2	I	T = 0	T = 0	R1	R1	R2	R2	all R	all R				

*Exposure ended prematurely due to complete degradation of samples

Table A4. Test protocol for original planned dates. 2 Cycles = R1, 4 cycles = R2. 10 Cycles = R4.

Schedule			10 panels each of 8 coating systems (80 panels total)
cycles	weeks	DATE	(SOW Task 3 Para 3)
0	0	5/8/2013	Measure EIS on 1 panel of each coating w/ traditional instrument and on 1 panel w/ portable system (16 panels total)
2	8	7/3/2013	Remove 2 panels of each coating (16 panels total) from cabinet exposure
			Conduct visual assessment via ASTM D610 and D714 of each panel
			Measure EIS on 1 panel of each coating w/ traditional instrument and on 1 panel w/ portable system (16 panels total)
4	16	8/28/2013	Remove 2 panels of each coating (16 panels total) from cabinet exposure
			Conduct visual assessment via ASTM D610 and D714 of each panel
			Measure EIS on 1 panel of each coating w/ traditional instrument and on 1 panel w/ portable system (16 panels total)
6 8	24 32	10/23/2013 12/16/2013	Remove 2 panels of each coating (16 panels total) from cabinet exposure
			Conduct visual assessment via ASTM D610 and D714 of each panel
			Measure EIS on 1 panel of each coating w/ traditional instrument and on 1 panel w/ portable system (16 panels total)
8 10	32 40	12/18/2013 2/10/2014	Remove 2 panels of each coating (16 panels total) from cabinet exposure
			Conduct visual assessment via ASTM D610 and D714 of each panel
			Measure EIS on 1 panel of each coating w/ traditional instrument and on 1 panel w/ portable system (16 panels total)

Table A5. Actual test dates for the indicated test procedures.

	date	Task 3.2			Task 3.3		
		cycle #	step		cycle #	step	
R1	3/13/2013	1	start B117	Analysis t = 0			
	3/27/2013	1	switch to QUV				
	4/10/2013	2	switch to B117				
	4/24/2013	2	switch to QUV				
	5/8/2013	3	switch to B117		1	start	Analysis t = 0
	5/22/2013	3	switch to QUV		1	Switch	
	6/5/2013	4	switch to B117		2	Switch	
	6/19/2013	4	switch to QUV		2	Switch	
R2	7/3/2013	5	switch to B117	Analysis t = 4 cycles (16 weeks)	3	Switch	Analysis t = 2 cycles (8 weeks)
	7/17/2013	5	switch to QUV		3	Switch	
	7/31/2013	6	switch to B117		4	Switch	
	8/14/2013	6	switch to QUV		4	Switch	
	8/28/2013	7	switch to B117		5	Switch	Analysis t = 4 cycles (16 weeks)
	9/11/2013	7	switch to QUV		5	Switch	
	9/25/2013	8	switch to B117		6	Switch	
	10/8/2013	TESTING INTERRUPTED			TESTING INTERRUPTED		
	10/9/2013	8	switch to QUV	-	6	Switch	-
	10/15/2013		start QUV @ Luna			start @ Luna	
	10/29/2013	8	switch to B117		6	Switch	
	11/12/2013	9	switch to QUV		7	Switch	
	11/26/2013	9	switch to B117		7	Switch	
	12/10/2013	10	switch to QUV		8	Switch	
	12/16/2013	10	End	Analysis t = 10 cycles (40 weeks)	8	Switch	Analysis t = 8 cycles (32 weeks)
	12/30/2013				9	Switch	
	1/13/2014				9	Switch	
	1/27/2014				10	Switch	
R4	2/10/2014				10	Switch	Analysis t = 10 cycles (40 weeks)
	2/24/2014				11	Switch	
	3/10/2014				11	Switch	
	3/24/2014				12	Switch	
	4/7/2014		All analysis completed		12	Switch	Analysis t = 12 cycles (48 weeks)
							Note: R3/R4 may be modified to consist solely of ASTM B117 depending on availability of QUV
							Note: R4 will occur either <u>after 10</u> or after 12 cycles depending on degradation of panels. The hope is that all panels have degraded enough to get good data from both instruments.

Figure A1. (a) Panel with grey coating finish and coated edges, (b) OCP vs. time for 1 hr full immersion prior to EIS test, (c) typical 3-electrode electrochemical cell used at University of Virginia, and (d) EIS results after different immersion times.

Figure A2. (a) The footprint of the copper plate CE used with the CHM device and the size of a flat cell window for a typical three electrode lab style EIS test setup. The EIS data (b) from the CHM system using the Gamry Reference 600 system for a coating which was (i) wet, (ii) dry, (iii) with silver-grease, and (iv) after 200 hr immersion in 5% NaCl solution.

a

b

Figure A3. Example of scanned panel A after R2 or 4 cycles =16 weeks, as follows:
 (a) scanned image, (b) image J, (c) calibration of image J against ASTM standard examples, and (d) table with ASTM grade and % rust for spots.

A calibration of the CHM against the Gamry Reference 600 was performed by using selected resistors as dummy cells, connected to the leads of either system in a 2-electrode arrangement (CE/RE vs. WE). This enabled 2-electrode impedance measurements to be made. The parallel resistors (R_t)

ranged from 1–10,000 M Ω ; or from 10^6 to 10^{10} ohms. This resistor was connected in parallel with a 1 nF capacitor and in series with a 10^2 ohm resistance in the (R(RC)) arrangement.

It can be seen in Figure A4 that the Gamry Reference 600 correctly tracks with the impedance of the circuit at all frequencies (solid symbols at all R_t levels from 10^6 to 10^{10} ohms). The Gamry Reference 600 correctly measures the capacitive impedance of 1 nF. The CHM data is not able to measure the 50 M Ω resistance but correctly measures the resistance at 10 M Ω and 1 M Ω (open symbols). At the R_t values of 50 M Ω and above, the CHM system records its published limit of 5×10^8 ohm. The 0.2–0.9 Hz frequency is too low to probe the 1 nF capacitor.

Figure A4. CHM and Gamry Reference 600 EIS spectra using an electrical equivalent circuit model (1 cm² area assumed).

Coating system I panels listed in Tables A1 and A3 were subjected to exposure cycles R0, R1, and R2 as identified in Tables A2 and A5. The panels were tested using the CHM copper electrode in both cases. Characterization and comparison of CHM to the Gamry Reference 600 system was conducted as well as optical imaging and visual rating according to ASTM D-610 and D-714. The visual appearance of the panels shown in Figure A5 indicates little damage. The ASTM ratings are shown in Tables A6 through A8 and discussed below.

Figure A5. Visual appearance of panel I0, I3, and I5 after the exposure periods listed.

The EIS results are summarized in Figures A6–A8. The EIS results from the Gamry Reference 600 were similar across all I-type coated panels at each exposure time, regardless of whether exposed continuously or removed at intervals. The R0 impedance data is mostly capacitive, with some resistive behavior at low frequency (lf) in both cases. The impedance data drops from R01 to R1 to R2 for I6 and I7. The EIS data remains similar for I0 to I5 for the individual samples. The drop for I5 at R2 is the greatest for the individual tests. The impedance values for I0 through I5 remain high, a finding which is consistent with the visual assessments that showed limited coating degradation.

The CHM results (shown as symbols and superimposed on EIS plots in Figures A6–A8) are not consistent with the Gamry Reference 600 results. Regarding I6, the EIS impedance remains at 5×10^8 ohms for R0 and R1 but drops to $2\text{--}3 \times 10^6$ ohms for R2. This is consistent with the dummy cell results where high impedance could not be detected but low impedance could, i.e., once the impedance of the coating system dropped below about 10^7 ohms. The results are the same over the 0.2–0.9 Hz frequency range. There is no further discussion of data at a specific CHM frequency since the data is all very similar to each other. The CHM results for I7 remained at 5×10^8 ohms or at the CHM instrument limit for R0 through R2. Similar

behavior was observed for coated panels I0-I5 where the impedance modulus remained at 5×10^8 ohms for the R0 through R2 cycles.

Figure A6. Comparison of CHM and Gamry Reference 600 impedance for I6 roofing panel after the R0–R2 cycles. EIS Bode magnitude and phase plots (top), with table of data at frequencies of 0.2, 0.5, and 0.9 Hz (bottom).

	Gamry Ref. 600			Electrowatch CHM		
	R0	R1	R2	R0	R1	R2
 Z - 0.2 Hz	1.40E+10	2.81E+07	28228.11	5.00E+08	5.00E+08	2.38E+06
Phase Angle - 0.2 Hz	-59.64038	-8.09815	0.20626	0	0	5
 Z - 0.5 Hz	7.55E+09	6.25E+07	31329.82	5.00E+08	5.00E+08	2.93E+06
Phase Angle - 0.5 Hz	-66.23121	-48.53644	0.01532	0	0	-10
 Z - 0.9 Hz	4.08E+09	6.09E+07	33424.93	5.00E+08	5.00E+08	2.71E+06
Phase Angle - 0.9 Hz	-67.64046	-86.78986	0.0898	0	0	-5

Figure A7. Comparison of CHM and Gamry Reference 600 impedance for I7 roofing panel after the R0–R2 cycles. EIS Bode magnitude and phase plots (top) and table of data at frequencies of 0.2, 0.5, and 0.9 Hz. (bottom).

	Gamry Ref. 600			Electrowatch CHM		
	R0	R1	R2	R0	R1	R2
 Z - 0.2 Hz	1.40E+10	9.09E7	1.74E8	5.00E+08	5.00E+08	5.00E+08
Phase Angle - 0.2 Hz	-59.64038	-12.07675	-62.41675	0	0	0
 Z - 0.5 Hz	7.55E+09	5.48E8	9.39E7	5.00E+08	5.00E+08	5.00E+08
Phase Angle - 0.5 Hz	-66.23121	-89.44404	-70.95644	0	0	0
 Z - 0.9 Hz	4.08E+09	1.79E8	4.84E7	5.00E+08	5.00E+08	5.00E+08
Phase Angle - 0.9 Hz	-67.64046	-126.8677	-76.06473	0	0	0

Figure A8. Comparison of CHM and Gamry Reference 600 impedance for I8 roofing panel after the R0–R2 cycles. EIS Bode magnitude and phase plots (top) and table of data at frequencies of 0.2, 0.5, and 0.9 Hz (bottom).

	Gamry Ref. 600						Electrowatch CHM					
	I0 - R0	I1 - R0	I2 - R1	I3 - R1	I4 - R2	I5 - R2	I0 - R0	I1 - R0	I2 - R1	I3 - R1	I4 - R2	I5 - R2
Z - 0.2 Hz	3.05E+09	2.91E+09	5.65E+09	1.04E+09	6.88E+08	1.09E+06	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08
Phase Angle - 0.2 Hz	-8.64E+01	-8.63E+01	-8.19E+01	-7.90E+01	-6.72E+01	-1.29E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Z - 0.5 Hz	1.45E+09	1.37E+09	2.75E+09	3.05E+08	3.69E+08	7.22E+05	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08
Phase Angle - 0.5 Hz	-8.67E+01	-8.59E+01	-8.39E+01	-8.12E+01	-7.31E+01	-8.81E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Z - 0.9 Hz	4.17E+08	3.47E+08	1.33E+09	1.51E+08	1.90E+08	6.96E+05	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08
Phase Angle - 0.9 Hz	-8.74E+01	-8.69E+01	-8.48E+01	-8.24E+01	-7.66E+01	-8.12E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

The phase angle results for the CHM compared to the Gamry Reference 600 were also inconsistent at various values (Figures A6–A8); the Gamry Reference 600 results indicated the phase angle behavior expected—that is, near 90 degrees for purely capacitive impedance and between 90 and 0 when resistance starts to appear in impedance data.

Visual observations were consistent with the Gamry Reference 600 results in that panel I6 retained an ASTM D610 rating of 10,³ while the D714 rating dropped from 8F to 7F over R0–R2 (Tables A6–A8). The I2–I5 panels' D610 ratings remained at 10, with less than 1% rust as detected by the image J analysis. This finding is consistent with high impedance and in this

³ The degree of rusting is evaluated using a 0–10 scale based on the percentage of visible surface rust.

sense, the CHM provided a qualitative indication of the high impedance of the coatings that compared well with the ASTM visual ratings.

Table A6. ASTM D610 and D714 ratings for panel type 10 for type A–H and panel 6 for type I.

		A				B				C				D				E				F				G				H				I	
		R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2
ASTM D610	visual	8S	7S	7S	7S	2P	1P	NA	NA	9S	9S	8S	8S	9S	9S	9S	8S	9S	8S	5S	5S	9S	8S	5S	5S	9S	8S	5S	4S	1P	1P	NA	NA	10	10
	ImageJ	6S	4S	4S	1S	0	0	NA	NA	6S	5S	5S	4S	7S	5S	2S	2S	5S	4S	3S	2S	6S	5S	3S	3S	6S	4S	3S	2S	0	0	NA	NA	10	10
ASTM D714	visual	8F	4F	4M	4M	5D	0	NA	NA	3F	3F	2F	2F	4F	4F	3F	3M	4F	4F	4M	4M	4F	4F	3F	2F	5F	5F	4F	3F	0	0	NA	NA	8F	7F

ImageJ ASTM D610 Analysis:

		A				B				C				D			
		R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4
ASTM D610	total area	23319680	24665088	23256192	23441280	24522176	24604928	NA	NA	23171840	23437184	23573760	23006720	23732160	23083008	22415616	23169024
	black area	402315	2427496	1893658	11377184	16901647	24052737	NA	NA	529212	1102448	1638493	2483642	117977	819582	8061728	8755645
	Rust %	1.73%	9.84%	8.14%	48.53%	68.92%	97.76%	NA	NA	2.28%	4.70%	6.95%	10.80%	0.50%	3.55%	35.96%	37.79%

		E				F				G				H				I	
		R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2
ASTM D610	total area	22639104	23745600	22542528	22755584	22169600	24137152	22700352	23414336	22083456	22498560	23086976	23210496	25233280	25284864	NA	NA	23000960	23289984
	black area	671598	2290503	5426501	7495293	304690	678196	4787997	4920112	353601	1644462	3950357	7658391	23860017	24800702	NA	NA	595	39482
	Rust %	2.97%	9.65%	24.07%	32.94%	1.37%	2.81%	21.09%	21.01%	1.60%	7.31%	17.11%	33.00%	94.56%	98.09%	NA	NA	0.00%	0.17%

Table A7. ASTM D-610 and D-714 ratings for panels # 2, 3, 4, 5, 6, 7, 8, 9 (individual) for A–H, and panel 2, 3, 4, 5 for I.

		A				B				C				D				E				F				G				H				I	
		R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2
ASTM D610	visual	8S	7S	7S	7S	2P	1P	NA	NA	9S	9S	8S	8S	9S	9S	9S	8S	9S	8S	5S	5S	9S	8S	5S	5S	9S	8S	5S	4S	1P	1P	NA	NA	10	10
	ImageJ	6S	4S	4S	1S	0	0	NA	NA	6S	5S	5S	4S	7S	5S	2S	2S	5S	4S	3S	2S	6S	5S	3S	3S	6S	4S	3S	2S	0	0	NA	NA	10	10
ASTM D714	visual	8F	4F	4M	4M	5D	0	NA	NA	3F	3F	2F	2F	4F	4F	3F	3M	4F	4F	4M	4M	4F	4F	3F	2F	5F	5F	4F	3F	0	0	NA	NA	8F	7F

ImageJ ASTM D610 Analysis:

		A				B				C				D			
		R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4
ASTM D610	total area	23319680	24665088	23256192	23441280	24522176	24604928	NA	NA	23171840	23437184	23573760	23006720	23732160	23083008	22415616	23169024
	black area	402315	2427496	1893658	11377184	16901647	24052737	NA	NA	529212	1102448	1638493	2483642	117977	819582	8061728	8755645
	Rust %	1.73%	9.84%	8.14%	48.53%	68.92%	97.76%	NA	NA	2.28%	4.70%	6.95%	10.80%	0.50%	3.55%	35.96%	37.79%

		E				F				G				H				I	
		R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2
ASTM D610	total area	22639104	23745600	22542528	22755584	22169600	24137152	22700352	23414336	22083456	22498560	23086976	23210496	25233280	25284864	NA	NA	23000960	23289984
	black area	671598	2290503	5426501	7495293	304690	678196	4787997	4920112	353601	1644462	3950357	7658391	23860017	24800702	NA	NA	595	39482
	Rust %	2.97%	9.65%	24.07%	32.94%	1.37%	2.81%	21.09%	21.01%	1.60%	7.31%	17.11%	33.00%	94.56%	98.09%	NA	NA	0.00%	0.17%

Table A8. ASTM D610 and D714 percentage rust stain for panels # 2 , 3, 4, 5, 6, 7, 8, and 9 (individual) for coating systems A–H, and panels 2, 3, 4, and 5 for coating system I.

		A								B							
		A2-R1	A3-R1	A4-R2	A5-R2	A6-R3	A7-R3	A8-R4	A9-R4	B2-R1	B3-R1	B4-R2	B5-R2	B6-R2.5	B7-R2.5	B8-R2.5	B9-R2.5
ASTM D610	total area	21545664	31928320	22357632	23831040	22571008	21821184	21905920	22697600	21201408	20810688	23500800	22989696	24413184	23988224	23639296	23309312
	black area	626226	518232	998193	585540	5716140	5358513	12185833	9248150	2414153	2599297	12286483	15052785	17764259	19410639	18433130	14229229
	Rust %	2.91%	1.62%	4.46%	2.46%	25.33%	24.56%	55.63%	40.75%	11.39%	12.49%	52.28%	65.48%	72.77%	80.92%	77.98%	61.05%

		C								D							
		C2-R1	C3-R1	C4-R2	C5-R2	C6-R3	C7-R3	C8-R4	C9-R4	D2-R1	D3-R1	D4-R2	D5-R2	D6-R3	D7-R3	D8-R4	D9-R4
ASTM D610	total area	22658048	22956352	22297600	22818048	21165760	22139712	22313728	22586880	20472064	21584896	21444352	21723840	22148032	21695808	23308992	22327680
	black area	788121	626861	970081	767286	3947156	1115792	2709716	3130073	257575	136777	1035459	3917163	9004290	8289730	14512936	15742021
	Rust %	3.48%	2.73%	4.35%	3.36%	18.65%	5.04%	12.14%	13.86%	1.26%	0.63%	4.83%	18.03%	40.66%	38.21%	62.26%	70.50%

		E								F							
		E2-R1	E3-R1	E4-R2	E5-R2	E6-R3	E7-R3	E8-R4	E9-R4	F2-R1	F3-R1	F4-R2	F5-R2	F6-R3	F7-R3	F8-R4	F9-R4
ASTM D610	total area	21127104	21880448	23117952	22502144	22472640	23216128	22916544	22280448	21121920	21559680	21814400	22045376	22230144	22109760	21947904	21997440
	black area	538753	1124158	1740887	1981256	3973020	6214357	6316529	6210177	548235	810274	704523	2186007	8062521	6155221	10917185	5168287
	Rust %	2.55%	5.14%	7.53%	8.80%	17.68%	26.77%	27.56%	27.87%	2.60%	3.76%	3.23%	9.92%	36.27%	27.84%	49.74%	23.49%

		G								H							
		G2-R1	G3-R1	G4-R2	G5-R2	G6-R3	G7-R3	G8-R4	G9-R4	H2-R1	H3-R1	H4-R2	H5-R2	H6-R2.5	H7-R2.5	H8-R2.5	H9-R2.5
ASTM D610	total area	22343040	22687808	22795776	22861056	23011328	22523904	22284288	22237056	23827200	23515008	23327744	23772800	24183168	24034048	23776256	23270464
	black area	666055	293663	3181356	2050491	6488656	8452220	11112646	13414529	19910840	20731429	22224554	23077846	23177582	23233962	22725967	22568323
	Rust %	2.98%	1.29%	13.96%	8.97%	28.20%	37.53%	49.87%	60.33%	83.56%	88.16%	95.27%	97.08%	95.84%	96.67%	95.58%	96.98%

		I			
		I2-R1	I3-R1	I4-R2	I5-R2
ASTM D610	total area	20865024	21299712	20697600	22071360
	black area	36263	37282	36765	38470
	Rust %	0.17%	0.18%	0.18%	0.17%

Coating systems A through H with the panel's identification numbers are listed in Table A3. Panels 0 and 11 were never exposed to the cyclic tests because they served as controls. Panels A10 through H10 were continuously exposed so, for example, A, B and C 10 etc., were continuously exposed and removed at the designated periods.

The tested exposure cycles were R0, R1, R2, R3 and R4 as identified in Tables A2, A4 and A5. Panels were tested using the CHM-supplied copper electrode in both cases. In the case of the Gamry Reference 600, the CE leads were connected to the copper electrode placed in the same location. Characterization and comparison of CHM to the Gamry Reference 600 system was conducted as well as optical imaging and visual rating according to ASTM D-610 and D-714. The ASTM ratings reported in Tables A6–A8 are discussed below.

The R0 impedance data was mostly capacitive with some resistive behavior at low frequency (lf) for some of the coatings. The impedance data comparing the CHM and Gamry Reference 600 behavior for panels A–H is documented with photos in Appendix C. The EIS results for the 3 x 6 inch test panels measured with the Gamry Reference 600 were similar across all type A–H coated panels, regardless of whether continuous exposures or removal at individual times. In other words, A10 behaved very similar to A0 through A9 as a set. However, the resistive behavior at R0 did not forecast later poor performance. The CHM data at 0.2, 0.5, and 0.9 Hz are reported as open symbols in Appendix D. The Gamry Reference 600 data are represented as closed symbols. The Gamry Reference 600 impedance data (Z modulus) drops the least from R0 to R4 for panel C. Panels G, F, and E exhibit mediocre behavior with impedance decreases and onset of resistive behavior from R0 to R4. The drop is significant for B and A, which are rated as poor. Panels D and H exhibited a severe drop in impedance and the coating performance was considered bad. In some cases these exposures were terminated early when rust covered the entire panel. These results are consistent with the visual assessments showing limited coating degradation for C and very bad visual ratings for A and B as well as D and H (Tables A6–A8).

The Gamry Reference 600 results with respect to samples that had surface contamination were not consistent depending on the coating system and contaminate. Samples C and F were the same coating with sample F consisting of a surface chloride contamination of 50 $\mu\text{g}/\text{cm}^2$. Sample C had

the least impedance decrease from R0 to R4 than sample F. Samples B and H were the same coating with sample H consisting of a surface contaminate of fine soil rubbed into the blasted surface. Like contaminated sample F, H had a greater decrease in impedance than B, even if both samples performed poorly. Conversely, sample G with a surface contaminate of flash rusting had a lower drop in impedance than sample A, which was the same coating on a clean blasted surface. These results show that the impedance level of a coating system does not definitively detect a possible coating system failure due to a surface contaminate.

The CHM results (shown as symbols and superimposed on EIS plots) were not consistent with the Gamry Reference 600 findings when the impedance was high. The CHM results were the same over the 0.2-0.9 Hz frequency range. There will be no further discussion of data at a specific CHM frequency since the data is basically unchanging at the different frequencies. For instance, a good match between CHM data and Gamry Reference 600 data is not seen for C, E, F and G where the CHM impedance remained at 5×10^8 ohms except for G at R4. This is consistent with the dummy cell results (Figure A4) where high impedance could not be read but low impedance could once the impedance of the coating system dropped below about $\sim 10^7$ ohms. The severe degradation of A and B as well as D and H were tracked somewhat better with the CHM because the impedance dropped below $\sim 10^7$ ohms. For instance, for panel A the impedance at R4 dropped to $2-4 \times 10^6$ ohms at a level where the CHM could make a measurement. The CHM results for panels such as C or G, F and E remained at 5×10^8 ohms or at the CHM instrument limit for R0 to R4. Panel C had the best impedance performance using the Gamry Reference 600 but could not be tracked with the CHM device.

The phase angle results for the CHM compared to the Gamry Reference 600 were also inconsistent at various values (Appendix D). In contrast, the Gamry Reference 600 results indicated the expected phase angle. That is, near 90 degrees for purely capacitive impedance and between 90 and 0 when resistance starts to appear in impedance data.

Visual findings were consistent with the Gamry Reference 600 results in that panel C retained a D-610 rating of 9S-8S, while the D-714 rating dropped from 3F to 3S. The panels with mediocre performance (e.g., panels E, F, and G) suffered degradation at the mounting holes and/or along the top edges which proved to be major flaws leading to significant rust

bleeding. This tended to invalidate the image J analysis (because rust bleeding could not be distinguished from coating damage). Panels E, F, and G dropped from an ASTM rating of 9S to 4 or 5S for R0 to R4. The ASTM D-714 rating changed from 4-5F to 2-4F. Panels A, B, and H performed the worst according to both the EIS and visual evaluations. The ASTM D-610 rating dropped to 1P in some cases. The ASTM D-714 rating dropped to 0 in the case of B and H, which is indicative of very poor performance.

It is clearly seen that results from the CHM and the Gamry Reference 600 are similar at 0.2, 0.5, and 0.9 Hz (Figure A9). It can also be seen that these frequencies are often in the resistive region. Therefore, similar impedance is seen at each frequency.

Figure A9. Impedance vs. cycle number at 0.2, 0.5 and 0.9 Hz for CHM (top) and Gamry Reference 600 (bottom) for panel A10.

The remainder of this discussion centers on a comparison of the CHM to the Gamry Reference 600. This comparison is divided into three cases. These include a very good coating with high impedance over the duration of the exposures, two mediocre coatings, and a very poor coating. The reason for this division is to assess the ability of the CHM to diagnose the electrical properties of the coating systems when the impedance remains high, drops slightly over the various cycles or drops considerably. The best performance was exhibited by coating C on the 3 x 6-inch test panels. The worst coatings were A, B, and D; and H was the poor coating. Coatings A and B were selected for further comparative analysis. The mediocre coatings included E, F and G. Coating E was selected for comparison. Regarding coating A, the EIS began to drop after R2 and the ASTM rating dropped at R2. The CHM measurement remained at 5×10^8 ohms and indicated a lower value when the impedance dropped below about $\sim 5 \times 10^7$ ohms. The ASTM J image rating is a false reading that reflects the high degree of rust bleeding from the top edge and the mounting hole in the panel. This was corrected in the visual measurement which attempted to subtract out this effect. Coating B behaved similarly. The CHM began to indicate the impedance when it dropped below $\sim 10^7$ ohms. The ASTM ratings dropped quickly to very low values. Once again the J image D-610 rating overestimated the damage. Regarding the best coating (C), the impedance remained high and the ASTM ratings also showed less pronounced decreases with increasing number of exposure cycles. The J image overestimated the true ASTM rating. The CHM system could not measure the impedance other than the instrument's upper limit of 5×10^8 ohms. Coating E behaved as a mediocre coating. The CHM and Gamry Reference 600 data were different where the CHM remained unchanged at 5×10^8 ohms, while the Gamry Reference 600 impedance changed with time. The ASTM ratings decreased monotonically with time.

In summary, most of the coating systems except A and B exhibited impedance values near 5×10^8 ohms or between 10^9 and 10^7 ohms. Unfortunately, the good to fair coatings exhibited impedance in this range as well and the CHM was unable to indicate the true impedance of these coating systems. Only the really poor coatings with impedance values that dropped below 10^7 - 10^6 ohms could be measured with any accuracy. Nevertheless, the CHM system is still very useful because upper limit impedance values of 5×10^8 ohms indicated a reasonable coating; and the very poor coatings were easily detected. However, the impedance of many field-deployed

coatings is in the range where measurements with the CHM appear difficult. Nowadays, a commercial, full EIS system may also be deployed in the field as long as electrical grounding requirements can be met and a portable power supply or generator capable of specified necessary AC power can be obtained.

The CHM in its current configuration is not capable of accurately measuring impedance values when they are above 5×10^7 ohms. In this situation the system indicates a default value of about 5×10^8 ohms, which is not the true impedance of the system. This cannot be interpreted as a wetting problem since the Gamry Reference 600 and CHM gave different impedance values for the same coating system and test area. The copper electrode without the silver paste worked adequately in a 2-electrode configuration, where the copper served as the counter electrode as well as the reference electrode. The impedance results with this 2-electrode arrangement were substantially similar to 3-electrode EIS tests when wetted by NaCl (as in laboratory salt-fog exposure) for long times, and when EIS measurements were made soon after test panel removal. Field testing verified that the present version of the CHM cannot measure the impedance of healthy coatings on steel and aluminum substructures. The accuracy of field measurements was not analyzed in this study. However, the laboratory testing indicated the ability of the CHM for measuring coating impedance values on the order of 10^7 ohms but erratic measurements in the field on healthy coating systems.

When the coating impedance falls below about 5×10^7 ohms, the CHM makes more precise measurements for the dummy cell but not so for coated test panels. Based on the dummy cell tests, the Gamry instrument could make valid measurements for all impedance values tested. The CHM would offer more utility when appreciable coating degradation is occurring. The test frequencies of the CHM are very close to each other; the results suggest that using any one of the three frequencies may be sufficient for collecting EIS data. The 0.2 Hz test frequency was selected in this test program. It is recommended that further development of the CHM should consider an option for including a 0.02 Hz or lower test frequency. This is based on previous work where the lowest frequency was necessary for evaluation of coating impedance; and a higher frequency for assessing coating capacitance. The EIS data for rapidly deteriorating coatings tracked well with the ASTM visual ratings provided that rust bleeding from the mounting holes in the test panels was taken into account. In the case of

good coatings that do not degrade as quickly, an impedance drop below about 10^7 – 10^6 ohms signals the onset of coating breakdown on steel structures and correlates with degree of corrosion determined from ASTM visual rating methods. This is similar to previous findings. However, some coating systems maintained high impedance values but the visual ASTM ratings dropped. This finding seems opposite to the expected trend, and it is attributed to rust bleeding from poorly coated edges and the poorly coated mounting holes in test panels. Unfortunately, these flaws were present in the as-received test panels.

Appendix B: Field Test Structure Section Locations

Central vehicle wash facility, Fort Bragg

Figure B1. Central vehicle wash facility test section 1 is located on top of the pipe, approximately 12 inches from the concrete exit of the northwestern corner of the wash facility.

Figure B2. Central vehicle wash facility test section 2 is located on the steel plate adjacent to location 1 and approximately 6 inches above the pipe.

Figure B3. Central vehicle wash facility test section 3 is located on the top and center of the T-coupler at the eastern end of the pipe.

Figure B4. Central vehicle wash facility test section 4 is located on the top flange adjacent to location 3.

82nd heating plant, Fort Bragg

Figure B5. Test section 1 of the 82nd heating plant fuel tank is located directly above the flange connecting to the inlet/outlet pipe at the northern part of the tank.

Figure B6. Test section 2 of the 82nd heating plant fuel tank is located on the tank flange below location 1.

Figure B7. Test section 3 of the 82nd heating plant fuel tank is located at the center of the easternmost access door.

Figure B8. Test section 4 of the 82nd heating plant fuel tank is located at the center of the southernmost access door.

Old Division water tower (C2714), Fort Bragg

Figure B9. Test section 1 of the old division water tower is located on the center leg, adjacent to the access door and to an existing coating failure.

Figure B10. Test section 2 of the old division water tower is located on the center leg access door, approximately 12 inches from the top of the door.

Figure B11. Test section 3 of the old division water tower is located on the top of the lower flange below the center leg access door.

Figure B12. Test section 4 of the old division water tower is located on the inside part of the most southeastern leg, approximately 12 inches above 3 foot flange.

New Division water tower (C7204), Fort Bragg

Figure B13. Test section 1 of the new division water tower is located on the inside area of the most eastern leg, approximately 12 inches below the horizontal weld and 6 inches to the left of the vertical weld.

Figure B14. Test section 2 of the new division water tower is located on the outside area of the most eastern leg, approximately 12 inches below the horizontal weld and 6 inches to the left of the vertical weld.

Figure B15. Test section 3 of the new division water tower is located on the outside area of the leg adjacent to the south of locations 1 and 2. It is approximately 12 inches below the horizontal weld and 6 inches to the left of the vertical weld.

Davis Hill water tower, Fort Lewis

Figure B16. Test section 1 of the Davis Hill water tower is located on the inner side of the north-eastern leg, 12 inches above the 3-foot flange and on the ridged area.

Figure B17. Test section 2 of the Davis Hill water tower is located on the center leg, approximately 4 in. from the service door flange and adjacent to the existing damaged coating.

Figure B18. Test section 3 of the Davis Hill water tower is located on the outer side of the north-eastern leg, 12 in. above the 3-foot flange and 12 in. left of the welded seam.

Figure B19. Test section 4 of the Davis Hill water tower is located on the eastern side of the southeastern leg, on the top of the 3-foot flange adjacent to the existing damaged coating.

E2C2 building roof, Fort Lewis

Figure B20. Aerial showing the four E2C2 building roof test locations.

Figure B21. Test Section 1 of the E2C2 building roof is located on the northern side of the roof, 12 inches from the bottom edge and approximately 21 feet from the western edge.

Figure B22. Test Section 2 of the E2C2 building roof is located on the northern side of the roof, 12 inches from the bottom edge and approximately 16 feet from the eastern edge.

Figure B23. Test Section 3 of the E2C2 building roof is located on the southern side of the roof, 12 inches from the bottom edge and approximately 21 feet from the western edge.

Figure B24. Test Section 4 of the E2C2 building roof is located on the southern side of the roof, 12 inches from the bottom edge and approximately 16 feet from the eastern edge.

Appendix C: Photos of Laboratory Test Panels and Detailed EIS Results of Panels

Figure C1. Visual condition of coating system A panels, from R0–R4.

Figure C2. Visual condition of coating system B panels, from R0–R2.

B0 at T = R0

B10 at T = R1

B10 at T = R2

B

Figure C3. Visual condition of coating system C panels, from R0-R4.

Figure C4. Visual condition of coating system D panels, from R0-R4.

Figure C5. Visual condition of coating system E panels, from R0-R4.

Figure C6. Visual condition of coating system F panels, from R0–R4.

Figure C7. Visual condition of coating system G panels, from R0–R4.

Figure C8. Visual condition of coating system H panels, from R0-R2.

H0 at T = R0

H10 at T = R1

H10 at T = R2

H

[illegible]

Figure C10. EIS data for CHM compared to Gamry Reference 600 for Panel A, continuous exposure.

A

continuous

Table C2. Tabulated data for Panel A is specifically for 0.2, 0.5, and 0.9 Hz.

	Gamry Ref. 600					Electrowatch CHM				
	A10 - R0	A10 - R1	A10 - R2	A10 - R3	A10 - R4	A10 - R0	A10 - R1	A10 - R2	A10 - R3	A10 - R4
- 0.2 Hz	9.35E+07	1.73E+08	1.19E+09	3.90E+04	1.15E+06	5.00E+08	5.00E+08	5.00E+08	5.40E+07	3.50E+07
∠ - 0.2 Hz	5.01E+00	9.67E+00	-6.29E+01	-5.92E+00	-5.35E+00	0.00E+00	0.00E+00	0.00E+00	-2.00E+01	-1.00E+01
- 0.5 Hz	2.48E+08	5.05E+08	6.52E+08	3.99E+04	1.15E+06	5.00E+08	5.00E+08	5.00E+08	4.07E+07	3.37E+07
∠ - 0.5 Hz	-3.33E+01	-7.48E+01	-7.06E+01	-5.00E+00	-6.49E+00	0.00E+00	0.00E+00	0.00E+00	-2.00E+01	0.00E+00
- 0.9 Hz	1.14E+08	2.59E+08	3.31E+08	4.00E+04	1.11E+06	5.00E+08	5.00E+08	5.00E+08	3.33E+07	3.24E+07
∠ - 0.9 Hz	2.67E+01	3.40E+01	-7.70E+01	-4.38E+00	-7.92E+00	0.00E+00	0.00E+00	0.00E+00	-3.00E+01	1.00E+01

Figure C11. EIS data for CHM compared to Gamry Reference 600 for Panel B, individual removals.

B

Individual removals

Table C3. Tabulated data for Panel B (individual) is specifically for 0.2, 0.5, and 0.9 Hz.

	Gamry Ref. 600										Electrowatch CHM									
	B0 - R0	B1 - R0	B2 - R1	B3 - R1	B4 - R2	B5 - R2	B6 - R2.5	B7 - R2.5	B8 - R2.5	B9 - R2.5	B0 - R0	B1 - R0	B2 - R1	B3 - R1	B4 - R2	B5 - R2	B6 - R2.5	B7 - R2.5	B8 - R2.5	B9 - R2.5
Z - 0.2 Hz	2.27E+08	4.64E+08	1.85E+09	1.14E+08	6.46E+07	3.02E+07	1.12E+10	1.03E+04	5.87E+08	9.64E+02	5.00E+08	5.00E+08	5.00E+08	2.80E+07	1.85E+07	4.68E+05	2.20E+06	3.87E+04	3.28E+05	2.55E+05
Phase Angle - 0.2 Hz	9.97E+00	-6.96E+01	-6.09E+01	2.86E+00	-1.15E+01	-2.88E+00	-6.33E+01	-1.46E-01	-1.53E+01	-3.50E-03	0.00E+00	0.00E+00	0.00E+00	1.00E+01	5.00E+00	-1.00E+01	5.00E+00	-5.00E+00	0.00E+00	-5.00E+00
Z - 0.5 Hz	1.27E+09	2.56E+08	1.01E+09	1.34E+08	4.55E+06	3.13E+07	6.07E+09	1.02E+04	5.82E+08	9.68E+02	5.00E+08	5.00E+08	5.00E+08	2.72E+07	1.75E+07	4.33E+05	2.28E+06	3.85E+04	3.08E+05	2.80E+05
Phase Angle - 0.5 Hz	9.40E+01	-7.21E+01	-6.96E+01	9.36E+00	-2.38E-01	1.97E+00	-7.16E+01	-1.33E-01	-1.83E+01	-2.53E-02	0.00E+00	0.00E+00	0.00E+00	1.00E+01	5.00E+00	-5.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Z - 0.9 Hz	1.35E+08	1.37E+08	5.27E+08	7.87E+07	3.57E+06	2.52E+07	3.15E+09	9.92E+03	5.36E+08	9.65E+02	5.00E+08	5.00E+08	5.00E+08	2.61E+07	1.70E+07	4.07E+05	2.32E+06	3.84E+04	9.25E+05	2.92E+05
Phase Angle - 0.9 Hz	7.88E+00	-7.51E+01	-7.68E+01	5.29E+01	1.35E+00	-3.03E+00	-7.67E+01	-1.51E-01	-2.32E+01	-2.36E-02	0.00E+00	0.00E+00	0.00E+00	2.00E+01	-2.50E+01	-5.00E+00	0.00E+00	-5.00E+00	2.00E+01	0.00E+00

Figure C12. EIS data for CHM compared to Gamry Reference 600 for Panel B, continuous exposure.

B continuous

Table C4. Tabulated data for Panel B (continuous) is specifically for 0.2, 0.5, and 0.9 Hz.

	Gamry Ref. 600					Electrowatch CHM				
	B10 - R0	B10 - R1	B10 - R2	B10 - R2.5	B10 - R2.5	B10 - R0	B10 - R1	B10 - R2	B10 - R2.5	B10 - R2.5
 Z - 0.2 Hz	2.27E+08	3.73E+04	7.97E+02	NA	NA	5.00E+08	2.73E+05	1.12E+06	NA	NA
Phase Angle - 0.2 Hz	9.97E+00	-4.28E+00	-5.02E+00	NA	NA	0.00E+00	0.00E+00	0.00E+00	NA	NA
 Z - 0.5 Hz	1.27E+09	3.65E+04	7.65E+02	NA	NA	5.00E+08	2.52E+05	9.73E+05	NA	NA
Phase Angle - 0.5 Hz	-9.40E+01	-4.04E+00	-5.58E+00	NA	NA	0.00E+00	-1.00E+01	-1.00E+00	NA	NA
 Z - 0.9 Hz	1.35E+08	3.57E+04	7.28E+02	NA	NA	5.00E+08	2.43E+05	9.39E+05	NA	NA
Phase Angle - 0.9 Hz	-7.88E+00	-3.89E+00	-6.00E+00	NA	NA	0.00E+00	-1.00E+01	-1.50E+01	NA	NA

Figure C13. EIS data for CHM compared to Gamry Reference 600 for Panel C, individual removals.

C individual

Figure C14. EIS data for CHM compared to Gamry Reference 600 for Panel C, continuous exposure.

C continuous

Table C6. Tabulated data for Panel C, continuous exposure, is specifically for 0.2, 0.5, and 0.9 Hz.

	Gamry Ref. 600					Electrowatch CHM				
	C10 - R0	C10 - R1	C10 - R2	C10 - R3	C10 - R4	C10 - R0	C10 - R1	C10 - R2	C10 - R3	C10 - R4
- 0.2 Hz	8.71E+08	3.90E+09	1.93E+09	8.52E+08	9.20E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08
∠ - 0.2 Hz	-2.61E+01	-6.74E+01	-5.02E+01	-6.00E+01	-6.75E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
- 0.5 Hz	1.10E+09	2.02E+09	1.19E+09	5.02E+08	5.07E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08
∠ - 0.5 Hz	-4.89E+01	-7.51E+01	-5.99E+01	-7.03E+01	-7.07E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
- 0.9 Hz	5.85E+08	1.01E+09	6.75E+08	2.67E+08	2.74E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08
∠ - 0.9 Hz	-8.64E+01	-8.71E+01	-8.75E+01	-8.20E+01	-8.07E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Figure C15. EIS data for CHM compared to Gamry Reference 600 for Panel D, individual removals.

D individual

Table C7. Tabulated data for Panel D, individual removals, is specifically for 0.2, 0.5, and 0.9 Hz.

	Gamry Ref. 600										Electrowatch CHM									
	D0 - R0	D1 - R0	D2 - R1	D3 - R1	D4 - R2	D5 - R2	D6 - R3	D7 - R3	D8 - R4	D9 - R4	D0 - R0	D1 - R0	D2 - R1	D3 - R1	D4 - R2	D5 - R2	D6 - R3	D7 - R3	D8 - R4	D9 - R4
Z - 0.2 Hz	6.14E+07	6.14E+07	4.66E+09	2.47E+07	1.63E+09	1.53E+08	8.20E+07	9.78E+07	4.72E+07	1.24E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.81E+07	5.00E+08	5.00E+08	5.00E+08	5.00E+08
Phase Angle - 0.2 Hz	-1.15E+01	-1.15E+01	-8.63E+01	1.08E+01	-6.96E+01	-4.60E+01	-2.79E+01	-1.95E+01	-1.86E+01	-1.24E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-1.50E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Z - 0.5 Hz	5.36E+07	5.36E+07	2.21E+09	3.52E+07	6.13E+08	9.80E+07	6.14E+07	7.45E+07	3.99E+07	1.11E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	4.90E+07	5.00E+08	5.00E+08	5.00E+08	5.00E+08
Phase Angle - 0.5 Hz	-3.14E+01	-3.14E+01	-8.65E+01	-7.67E+01	-8.19E+01	-5.23E+01	-3.24E+01	-2.19E+01	-2.45E+01	-1.71E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Z - 0.9 Hz	2.87E+07	2.87E+07	1.05E+09	2.28E+07	2.49E+08	6.05E+07	4.38E+07	5.77E+07	3.19E+07	9.50E+07	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	3.82E+07	5.00E+08	5.00E+08	5.00E+08	5.00E+08
Phase Angle - 0.9 Hz	8.22E+01	8.22E+01	-8.60E+01	1.78E+02	-8.87E+01	-5.71E+01	-3.95E+01	-2.46E+01	-3.19E+01	-2.37E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-4.50E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Figure C16. EIS data for CHM compared to Gamry Reference 600 for Panel D, continuous exposure.

D continuous

Table C8. Tabulated data for Panel D, continuous exposure, is specifically for 0.2, 0.5, and 0.9 Hz.

	Gamry Ref. 600					Electrowatch CHM				
	D10 - R0	D10 - R1	D10 - R2	D10 - R3	D10 - R4	D10 - R0	D10 - R1	D10 - R2	D10 - R3	D10 - R4
- 0.2 Hz	6.14E+07	6.13E+09	1.90E+09	6.17E+08	3.01E+07	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08
∠ - 0.2 Hz	-1.15E+01	-8.65E+01	-3.71E+01	-4.81E+01	-7.22E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
- 0.5 Hz	5.36E+07	2.92E+09	1.30E+09	3.85E+08	2.91E+07	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08
∠ - 0.5 Hz	-3.14E+01	-8.64E+01	-5.31E+01	-5.91E+01	-9.78E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
- 0.9 Hz	2.87E+07	1.39E+09	7.52E+08	2.42E+08	2.65E+07	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08
∠ - 0.9 Hz	8.22E+01	-8.56E+01	-6.51E+01	-7.80E+01	-1.36E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Figure C17. EIS data for CHM compared to Gamry Reference 600 for Panel E, individual removals.

E individual

Figure C18. EIS data for CHM compared to Gamry Reference 600 for Panel E, continuous exposure.

E continuous

Table C9. Tabulated data for Panel E, continuous exposure, is specifically for 0.2, 0.5, and 0.9 Hz.

	Gamry Ref. 600					Electrowatch CHM				
	E10 - R0	E10 - R1	E10 - R2	E10 - R3	E10 - R4	E10 - R0	E10 - R1	E10 - R2	E10 - R3	E10 - R4
- 0.2 Hz	1.54E+08	2.30E+09	1.45E+08	1.31E+08	5.01E+07	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08
∠ - 0.2 Hz	-2.30E+01	-6.22E+01	-4.97E+01	-4.01E+01	-1.54E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
- 0.5 Hz	2.52E+08	1.66E+09	9.56E+07	8.93E+07	4.34E+07	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08
∠ - 0.5 Hz	5.16E+01	-4.95E+01	-5.57E+01	-4.77E+01	-2.12E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
- 0.9 Hz	9.65E+07	6.01E+08	5.91E+07	5.72E+07	3.53E+07	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08
∠ - 0.9 Hz	-6.42E+01	-9.80E+01	-6.05E+01	-5.45E+01	-2.77E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Figure C19. EIS data for CHM compared to Gamry Reference 600 for Panel F, individual removals.

Table C10. Tabulated data for Panel F, individual removals, is specifically for 0.2, 0.5, and 0.9 Hz.

[illegible][illegible]

C20. EIS data for CHM compared to Gamry Reference 600 for Panel F, continuous exposure.

F continuous

Table C11. Tabulated data for Panel F, continuous exposure, is specifically for 0.2, 0.5, and 0.9 Hz.

	Gamry Ref. 600					Electrowatch CHM				
	F10 - R0	F10 - R1	F10 - R2	F10 - R3	F10 - R4	F10 - R0	F10 - R1	F10 - R2	F10 - R3	F10 - R4
- 0.2 Hz	4.19E+09	2.75E+08	2.77E+09	6.26E+08	6.36E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08
∠ - 0.2 Hz	-8.82E+01	-2.08E+01	-8.51E+01	-5.41E+01	-3.72E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
- 0.5 Hz	2.01E+09	4.22E+08	1.33E+09	3.88E+08	4.38E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08
∠ - 0.5 Hz	-8.74E+01	-6.09E+01	-8.54E+01	-6.08E+01	-4.93E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
- 0.9 Hz	9.50E+08	3.27E+08	6.45E+08	2.14E+08	2.70E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08
∠ - 0.9 Hz	-8.64E+01	-1.15E+02	-8.49E+01	-6.56E+01	-5.95E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Figure C22. EIS data for CHM compared to Gamry Reference 600 for Panel G, continuous exposure.

G continuous

Table C13. Tabulated data for Panel G, continuous exposure, is specifically for 0.2, 0.5, and 0.9 Hz.

	Gamry Ref. 600					Electrowatch CHM				
	G10 - R0	G10 - R1	G10 - R2	G10 - R3	G10 - R4	G10 - R0	G10 - R1	G10 - R2	G10 - R3	G10 - R4
- 0.2 Hz	3.71E+09	2.29E+07	2.22E+09	7.34E+08	4.84E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	1.98E+07
∠ - 0.2 Hz	-8.76E+01	-6.92E+00	-7.38E+01	-6.56E+01	-1.94E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.00E+00
- 0.5 Hz	1.76E+09	1.16E+08	1.15E+09	4.04E+08	4.14E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	3.16E+07
∠ - 0.5 Hz	-8.74E+01	1.71E+02	-7.56E+01	-7.14E+01	-3.26E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.00E+00
- 0.9 Hz	8.32E+08	5.80E+07	6.06E+08	2.13E+08	2.97E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	3.87E+07
∠ - 0.9 Hz	-8.65E+01	7.24E+01	-7.63E+01	-7.61E+01	-4.88E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-5.00E+00

Figure C23. EIS data for CHM compared to Gamry Reference 600 for Panel H, continuous exposure.

H individual

Figure 24. EIS data for CHM compared to Gamry Reference 600 for Panel H, continuous exposure.

H continuous

Table C14. Tabulated data for Panel G, continuous exposure, is specifically for 0.2, 0.5, and 0.9 Hz.

	Gamry Ref. 600					Electrowatch CHM				
	H10 - R0	H10 - R1	H10 - R2	H10 - 2.5	H10 - R2.5	H10 - R0	H10 - R1	H10 - R2	H10 - R2.5	H10 - R2.5
0.2 Hz	3.16E+08	7.13E+07	1.70E+04	NA	NA	5.00E+08	4.02E+03	7.09E+04	NA	NA
0.2 Hz	-4.43E+01	-3.32E+00	-3.18E+00	NA	NA	0.00E+00	0.00E+00	-5.00E+00	NA	NA
0.5 Hz	3.92E+08	1.19E+08	1.64E+04	NA	NA	5.00E+08	4.16E+03	7.09E+04	NA	NA
0.5 Hz	-1.47E+01	-4.65E+00	-3.46E+00	NA	NA	0.00E+00	0.00E+00	-5.00E+00	NA	NA
0.9 Hz	1.82E+08	1.68E+08	1.59E+04	NA	NA	5.00E+08	5.21E+03	6.99E+04	NA	NA
0.9 Hz	1.27E+01	-8.64E+00	-3.80E+00	NA	NA	0.00E+00	0.00E+00	-5.00E+00	NA	NA

Appendix D: Field Test Results from the CHM

Figure D1. Old Division water tower (C2714), Fort Bragg, test location 1 impedance results from the CHM in ohms/cm².

	Frequency	Z 0.2 Hz	Z 0.5 Hz	Z 0.9 Hz
Month	0	5.97E+06	6.20E+06	9.86E+06
	6	5.00E+08	5.00E+08	5.00E+08
	12	1.19E+06	2.56E+06	1.31E+06
	18	4.75E+06	1.24E+07	5.00E+08

Figure D2. Old Division water tower (C2714), Fort Bragg, test location 2 impedance results from the CHM in ohms/cm².

	Frequency	Z 0.2 Hz	Z 0.5 Hz	Z 0.9 Hz
Month	0	4.41E+06	1.23E+07	3.30E+07
	6	2.98E+07	4.82E+07	2.71E+07
	12	3.19E+02	3.24E+02	3.23E+02
	18	2.63E+07	3.60E+07	5.69E+06

Figure D3. Old Division water tower (C2714), Fort Bragg, test location 3 impedance results from the CHM in ohms/cm².

	Frequency	Z 0.2 Hz	Z 0.5 Hz	Z 0.9 Hz
Month	0	1.61E+06	2.25E+06	2.80E+06
	6	2.32E+07	1.45E+08	9.99E+06
	12	2.10E+07	5.00E+08	3.24E+02
	18	3.16E+06	7.32E+06	7.98E+05

Figure D4. Old Division water tower (C2714), Fort Bragg, test location 4 impedance results from the CHM in ohms/cm².

	Frequency	Z 0.2 Hz	Z 0.5 Hz	Z 0.9 Hz
Month	0	4.35E+05	5.26E+05	6.62E+05
	6	1.02E+07	1.03E+07	1.04E+07
	12	2.35E+06	3.06E+06	3.25E+06
	18	5.12E+07	1.63E+07	1.64E+06

Figure D5. Central vehicle wash facility, Fort Bragg, test location 1 impedance results from the CHM in ohms/cm².

	Frequency	Z 0.2 Hz	Z 0.5 Hz	Z 0.9 Hz
Month	0	9.17E+06	1.51E+07	1.02E+07
	6	1.64E+05	1.24E+05	1.12E+05
	12	5.91E+05	5.27E+05	5.29E+05
	18	5.09E+04	7.80E+04	2.58E+04

Figure D6. Central vehicle wash facility, Fort Bragg, test location 2 impedance results from the CHM in ohms/cm².

	Frequency	Z 0.2 Hz	Z 0.5 Hz	Z 0.9 Hz
Month	0	5.39E+05	4.84E+05	4.87E+05
	6	1.91E+07	2.94E+06	4.03E+06
	12	3.62E+06	3.72E+06	3.76E+06
	18	5.00E+08	2.47E+06	4.50E+06

Figure D7. Central vehicle wash facility, Fort Bragg, test location 3 impedance results from the CHM in ohms/cm².

	Frequency	Z 0.2 Hz	Z 0.5 Hz	Z 0.9 Hz
Month	0	1.92E+06	1.66E+06	1.85E+06
	6	6.79E+05	6.49E+05	5.59E+05
	12	1.27E+06	1.13E+06	1.09E+06
	18	4.76E+05	3.32E+05	2.82E+05

Figure D8. Central vehicle wash facility, Fort Bragg, test location 4 impedance results from the CHM in ohms/cm².

	Frequency	Z 0.2 Hz	Z 0.5 Hz	Z 0.9 Hz
Month	0	1.41E+06	1.66E+06	1.77E+06
	6	4.50E+05	2.75E+05	2.43E+05
	12	1.13E+06	1.33E+06	1.41E+06
	18	1.63E+05	3.06E+05	5.11E+05

Figure D9. 82nd heat distribution plant fuel tank, Fort Bragg, test location 1
impedance results from the CHM in ohms/cm².

	Frequency	Z 0.2 Hz	Z 0.5 Hz	Z 0.9 Hz
Month	0	1.47E+07	9.52E+06	7.37E+07
	6	9.77E+06	1.00E+07	9.97E+06
	12	2.21E+06	2.21E+06	2.21E+06
	18	1.41E+07	9.49E+06	8.21E+06

Figure D10. 82nd heat distribution plant fuel tank, Fort Bragg, test location 2 impedance results from the CHM in ohms/cm².

	Frequency	Z 0.2 Hz	Z 0.5 Hz	Z 0.9 Hz
Month	0	7.77E+06	7.73E+06	7.71E+06
	6	5.00E+08	1.82E+08	1.73E+08
	12	5.00E+08	5.00E+08	5.00E+08
	18	5.00E+08	5.00E+08	5.00E+08

Figure D11. 82nd heat distribution plant fuel tank, Fort Bragg, test location 3
impedance results from the CHM in ohms/cm².

	Frequency	Z 0.2 Hz	Z 0.5 Hz	Z 0.9 Hz
Month	0	1.14E+07	1.28E+07	1.38E+07
	6	5.00E+08	8.63E+07	2.59E+07
	12	2.30E+07	3.58E+07	3.97E+07
	18	3.15E+08	2.01E+07	2.39E+07

Figure D12. 82nd heat distribution plant fuel tank, Fort Bragg, test location 4 impedance results from the CHM in ohms/cm².

	Frequency	Z 0.2 Hz	Z 0.5 Hz	Z 0.9 Hz
Month	0	1.83E+07	5.00E+08	5.00E+08
	6	5.00E+08	5.00E+08	5.00E+08
	12	5.00E+08	5.00E+08	5.00E+08
	18	5.00E+08	5.00E+08	5.00E+08

Figure D13. E2C2 building roof, Fort Lewis, test location 1 impedance results from the CHM in ohms/cm².

	Frequency	Z 0.2 Hz	Z 0.5 Hz	Z 0.9 Hz
Month	0.0	3.55E+07	3.37E+07	3.30E+07
	6.0	2.93E+07	2.24E+07	1.49E+07
	12.0	5.00E+08	1.18E+07	1.16E+07
	18.0	3.59E+06	1.00E+06	2.91E+06

Figure D14. E2C2 building roof, Fort Lewis, test location 2 impedance results from the CHM in ohms/cm².

	Frequency	Z 0.2 Hz	Z 0.5 Hz	Z 0.9 Hz
Month	0.0	1.09E+07	1.09E+07	1.08E+07
	6.0	2.85E+07	1.65E+07	1.88E+07
	12.0	2.81E+07	2.06E+07	1.50E+07
	18.0	3.35E+07	1.91E+06	8.14E+06

Figure D15. E2C2 building roof, Fort Lewis, test location 3 impedance results from the CHM in ohms/cm².

	Frequency	Z 0.2 Hz	Z 0.5 Hz	Z 0.9 Hz
Month	0.0	1.63E+05	1.16E+05	9.35E+04
	6.0	3.37E+07	3.50E+07	1.86E+07
	12.0	5.18E+07	2.15E+07	1.54E+07
	18.0	2.10E+07	2.09E+07	2.14E+06

Figure D16. E2C2 building roof, Fort Lewis, test location 4 impedance results from the CHM in ohms/cm².

	Frequency	Z 0.2 Hz	Z 0.5 Hz	Z 0.9 Hz
Month	0.0	4.87E+07	3.14E+07	1.97E+07
	6.0	2.49E+07	1.81E+07	1.55E+07
	12.0	2.44E+07	3.21E+07	1.51E+07
	18.0	3.20E+07	1.42E+07	1.24E+07

Figure D17. Davis Hill water tower, Fort Lewis, test location 1 impedance results from the CHM in ohms/cm².

	Frequency	Z 0.2 Hz	Z 0.5 Hz	Z 0.9 Hz
Month	0.0	5.00E+08	1.18E+07	1.16E+07
	12.0	7.80E+06	1.53E+07	1.38E+07
	18.0	5.00E+08	2.22E+06	2.21E+06

Figure D18. Davis Hill water tower, Fort Lewis, test location 2 impedance results from the CHM in ohms/cm².

	Frequency	Z 0.2 Hz	Z 0.5 Hz	Z 0.9 Hz
Month	0.0	2.81E+07	2.06E+07	1.50E+07
	12.0	1.62E+07	1.51E+07	1.37E+07
	18.0	5.00E+08	5.00E+08	5.00E+08

Figure D19. Davis Hill water tower, Fort Lewis, test location 3 impedance results from the CHM in ohms/cm².

	Frequency	Z 0.2 Hz	Z 0.5 Hz	Z 0.9 Hz
Month	0.0	5.18E+07	2.15E+07	1.54E+07
	12.0	5.00E+08	5.00E+08	5.00E+08
	18.0	1.35E+08	5.00E+08	5.00E+08

Figure D20. Davis Hill water tower, Fort Lewis, test location 4 impedance results from the CHM in ohms/cm².

	Frequency	Z 0.2 Hz	Z 0.5 Hz	Z 0.9 Hz
Month	0.0	2.44E+07	3.21E+07	1.51E+07
	12.0	3.23E+02	3.22E+02	3.22E+02
	18.0	5.00E+08	5.00E+08	5.00E+08

Appendix E: Suggested Improvements to the Coating Health Monitor (CHM)

The following are recommendations that might produce a CHM system that would provide the sought-after benefits.

Testing

A key issue that needs to be addressed is the method of wetting in order to facilitate impedance measurements, and the impact of drying on such measurements. These issues have been explored both in the literature and in the present study. Further studies should be undertaken to understand the optimal time of wetting before an EIS measurement is made and how it influences the results. Another other issue is how many areas to test and whether or not the results become biased by a defect that is rare. Running measurements on multiple areas at the same time would be reasonable, but the exact methodology needs to be addressed.

Instrumentation development

The CHM device cannot measure the true impedance above $\sim 10^7$ ohms. All very good coatings with impedance values above this level are recorded as 5×10^8 ohms. Unfortunately only coatings with impedance values below $\sim 10^7$ ohms can be measured and monitored versus time. Nevertheless, the copper electrode and clamping device are valuable for field measurements with a portable instrument. The CHM can examine the “go” and “no go” aspects of coatings by recording poor low-frequency impedance values $< 10^7$ ohms and may work in situations with an electrically grounded working electrode (WE).

It is highly recommended that the present CHM instrument be modified to expand its upper impedance measurement limit to 10^9 ohms, enable valid phase angle de-termination, and vary the frequency over a range from 0.001 or 0.01 Hz up to 1 Hz and then to 10,000 Hz when using a few frequencies or, better still, provide information over a full frequency range from 0.001 to 20,000 Hz. This would enable the low-frequency complex impedance data to be obtained as well as other impedance parameters such as the breakpoint frequency and coating capacitance, both of which can often provide additional insight on coating degradation.

On the other hand, commercial instruments controlled from a laptop computer should now be easily field deployable with an AC voltage inverter operating off a gas-powered generator and/or a battery back. The only issue is how well the system works with a grounded WE. Instrument manufacturers claim the capability to deliver potentiostats such that the WE can be grounded.

The recommended data analysis approach is limited by these restrictive findings. Only the low-frequency impedance data can be used currently.

Data analysis

It is recommended that impedance measurements be taken for a range of wetting times and over a broader frequency range to optimize testing procedure and data analysis. It is recommended that several areas of a coating be tested, and a cumulative probability plot be constructed.

Future means of implementation

Additional data is essential to determine the effects of different coating systems, thicknesses, and substrate materials on impedance measurements before a comprehensive condition-based coatings health monitoring system can be developed and implemented. Figure E1 is an example of the parameters that could be utilized for coating impedance measurements and monitoring coating health.

Service life prediction would have to be determined from conducting a trend analysis of EIS data collected over time. The rate of coating degradation can vary based on climate, environmental conditions, substrate, and the coating system. It is probable that life cycle prediction would have to be performed on a case-by-case basis rather than using a single model. However, additional testing and analysis is required to determine if a finite algorithm could be developed applied for correlating coating impedance measurements and expected life cycle.

Figure E1. Potential condition-based maintenance of coating systems, dependent on EIS measurements.

Impedance [Z], Ohms/cm ²	Coating Condition
$> 10^8$	Excellent
$10^7 - 10^8$	Good
$10^5 - 10^7$	Moderate
$< 10^5$	Poor

Excellent	Coating system is providing excellent corrosion prevention as designed. No action required.
Good	Coating system is beginning to degrade; however corrosion prevention is adequate. Begin to closely monitor for continued degradation.
Moderate	Coating system is expected to be showing visual signs of degradation. Corrosion protection may become limited in subsequent years. Consider scheduling an overcoat before additional degradation.
Poor	Coating system may no longer be providing acceptable corrosion prevention. Remove and replacement should be scheduled.

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14. ABSTRACT The Department of Defense maintains many steel structures that are subject to corrosion. Coatings are a traditional first line of defense against corrosion, but a completely accurate assessment of coating condition cannot always be made by using only conventional visual inspection techniques because not all defects are visible. Alternatively, performing laboratory inspections can be difficult, time-consuming, costly, and may require testing specimens separately from the actual coated structure. This Office of the Secretary of Defense Corrosion Prevention and Control Program project sought to improve accuracy and lower costs (early detection of problems reduce future maintenance) by demonstrating and validating the capabilities of a portable electrochemical impedance spectroscopy (EIS) technology for evaluating coating health. A portable EIS system was demonstrated in a laboratory setting and at field locations on Fort Bragg, NC, and Fort Lewis, WA. The results showed the tested version of the portable EIS system has limited capabilities in comparison to traditional laboratory methods. Based on the results of the technology demonstration, the system needs further development before the anticipated benefits might be realized. Therefore, widespread implementation of the demonstrated system is not recommended at the current state, and the project's return on investment is considered to be zero.					
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