ERDC/CERL TR-16-20

US Army Corps of Engineers®
Engineer Research and Development Center

ERDC
INNOVATIVE SOLUTIONS for a safer, better world

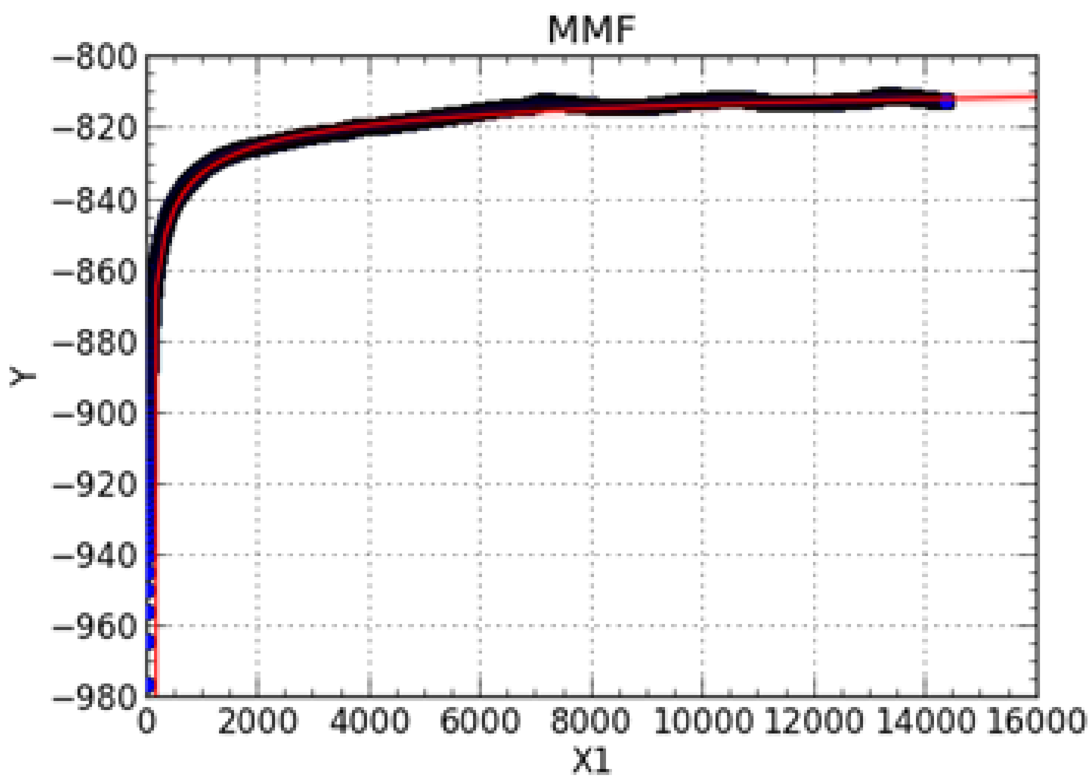
DoD Corrosion Prevention and Control Program

Polarization Decay Fit for Assured Cathodic Protection of Steel Structures

Final Report on Project F12-AR03

Thomas A. Carlson, Andrew P. Friedl, Charles P. Marsh, James P. Miller, James B. Bushman, Robert Bushman, and Bopinder S. Phull

September 2016



Approved for public release; distribution is unlimited.

Construction Engineering Research Laboratory

The US Army Engineer Research and Development Center (ERDC) solves the nation's toughest engineering and environmental challenges. ERDC develops innovative solutions in civil and military engineering, geospatial sciences, water resources, and environmental sciences for the Army, the Department of Defense, civilian agencies, and our nation's public good. Find out more at www.erdc.usace.army.mil.

To search for other technical reports published by ERDC, visit the ERDC online library at http://acwc.sdp.sirsi.net/client/default.

Polarization Decay Fit for Assured Cathodic Protection of Steel Structures

Final Report on Project F12-AR03

Thomas A. Carlson, Andrew P. Friedl, Charles P. Marsh, and James P. Miller

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

James B. Bushman, Robert Bushman, and Bopinder S. Phull

Bushman & Associates, Inc.
P.O. Box 425
Medina, OH 44258

Final report

Approved for public release; distribution is unlimited.

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

Under Project F12-AR03, "Polarization and/or Decay Fit for Assured Impressed Current Protection"

Abstract

Corrosion is the number-one cause of damage to industrial waste lines, potable water distribution systems, heat distribution pipes, and underground storage tanks. Besides costing millions of dollars annually to repair, corrosion at military installations can adversely impact mission objectives through the catastrophic failure of mission-critical infrastructure. This project sought to develop a technology to quickly and more reliably predict the achievement of the NACE International 100 mV polarization shift cathodic protection criterion for large metallic structures. By basing the prediction on sufficient initial short-term data, any error associated with long-term environmental changes (e.g., moisture, temperature changes, and soil compaction) is avoided. Time savings for reduced measurement labor is a related benefit. Overall, the technology was validated at a proof-of-principle level. While not yet ready for immediate implementation, the technology merits further coordinated development. Wider testing and field demonstration, followed by a concerted and long-term criteria acceptance effort, are still required. Once fully implemented, the projected return on investment is projected to be 8.55.

DISCLAIMER: The contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products. All product names and trademarks cited are the property of their respective owners. The findings of this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

DESTROY THIS REPORT WHEN NO LONGER NEEDED. DO NOT RETURN IT TO THE ORIGINATOR.

Contents

Figures and Tables

Figures

Tables

Preface

This demonstration was performed for the Office of the Secretary of Defense (OSD) under Department of Defense (DoD) Corrosion Prevention and Control Project F12-AR03, “Polarization and/or Decay Fit for Assured Impressed Current Protection,” Military Interdepartmental Purchase Request (MIPR) DSAM20389, dated 3 February 2012. The proponent was the U.S. Army Office of the Assistant Chief of Staff for Installation Management (ACSIM), and the stakeholder was the U.S. Army Installation Management Command (IMCOM). The technical monitors were Daniel J. Dunmire (OUSD(AT&L)), Bernie Rodriguez (IMPW-E), and Valerie D. Hines (DAIM-ODF).

The work was performed by the Materials and Structures Branch (CEERD-CFM), Facilities Division (CF), U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL). Significant portions of this work were performed by Bushman & Associates of Medina, OH, and monitored by ERDC-CERL. At the time of publication, Vicki L. Van Blaricum was Chief, CEERD-CFM; Donald K. Hicks was Chief, CEERD-CF; and Kurt Kinnevan, CEERD-CZT, was the Technical Director for Adaptive and Resilient Installations. The Deputy Director of ERDC-CERL was Dr. Kirankumar Topudurti, and the Director was Dr. Ilker Adiguzel.

The contributions of subcontractors David Franklin (MSE-TA Applications of Butte, MT) and Terry Wamsley (Hach Co., Loveland, CO) are acknowledged. Matthew Ziemann of ERDC-CERL provided input on return-on-investment calculations.

The following installation personnel are also gratefully acknowledged for their support and assistance in this project:

- J.D. Bales – Directorate of Public Works, Fort Leonard Wood
- Bill Rafferty – USACE District Office, Omaha, NE

The Commander of ERDC was COL Bryan S. Green and the Director was Dr. Jeffery P. Holland.

Executive Summary

Impressed current and galvanic cathodic protection (CP) systems, when used in conjunction with improved coating systems, are capable of providing corrosion protection to large metallic structures. However, periodic monitoring is required to ensure that metallic structures remain sufficiently polarized for effective corrosion protection in accordance with NACE International standards. For decades there has been a need for a more reliable and faster way to monitor the polarization status of cathodically protected buried and submerged ferrous structures. In addition to requiring many hours of labor, typical methods of testing CP system effectiveness require extended time frames that can significantly compromise the data. The measurement of polarization gain or decay (indicative of having previously achieved sufficient polarization) resulting from the application of CP systems is one of the two primary criteria for assessing whether effective CP has been achieved. Furthermore, on many structures, it is the only criterion that can be used.

Polarization readings can be shifted significantly with changes in environmental moisture, temperature, and even traffic around the structure. Therefore, polarization data can erroneously show increases or decreases in decay rates purely due to passing rain storms or the difference in temperature from midday to midnight, thus adversely impacting the reliability of monitoring. This process is further complicated as the size of structures being tested increases, as in the case of pipelines that run many miles or the case of when a structure's coating quality deteriorates over time. Using methods currently available, the measurement of polarization gain or decay can take 24 hours or more at each location being monitored, and multiple trips to each test site are often required to determine if the criterion has been met.

The Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL) proposed to the Office of the Secretary of Defense (OSD) to create a prototype electronic device to aid the development and validation of a polarization curve fit and predictive algorithm. This project successfully developed a technology capable of taking a reliable and predictive snapshot of a structure's polarization in a matter of minutes, with the added benefit of eliminating the possibility of changes in the environment skewing the data collected over a longer time and giving a false indication of the state of cathodic protection.

Unit Conversion Factors

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

1 Introduction

1.1 Problem statement

Corrosion is the number-one cause of damage to industrial waste lines, potable water distribution systems, heat distribution pipes, above-ground storage tanks (on grade and elevated), and underground storage tanks (USTs). Besides costing millions of dollars annually to repair, corrosion at military installations can adversely impact mission objectives through the catastrophic failure of mission-critical infrastructure. It has been estimated that corrosion-related economic losses in the United States now amount to about $1 trillion per year [1].

Cathodic protection (CP) is a well-established, widely practiced electrochemical technique for corrosion control of numerous buried and immersed steel structures, including pipelines, storage tanks, ship hulls, rebar in concrete, and hot water heaters. If properly designed, monitored, and maintained, CP is the only technique that can completely prevent corrosion. Protective coatings alone cannot completely prevent corrosion. Nevertheless, coatings serve as a valuable supplement to CP wherever the latter is applicable. While providing partial corrosion protection, coatings also serve to reduce the net amount of CP current required. The direct current (DC) required for CP can be supplied either from sacrificial anodes, impressed-current cathodic protection (ICCP) systems, or a combination of both. Protected structures must be monitored periodically as described for example, in NACE International Standards—(Standard Practice) SP0169 [2] and (Test Method) TM0497 [3]— to determine the effectiveness of the structure's CP.

One of the criteria for determining CP efficacy, and the only one that can be used on some structures (e.g., typically larger ones), is to achieve 100 mV of polarization shift. Polarization shift is established by purposefully directing a positive and sufficiently large DC to terminate on the structure to be protected. This positive current travels through an electrolyte, consisting typically of either water or moist soil. Associated transport of negative carriers—electrons—occurs in the metallic structure and attached conducting wires.

Naturally occurring corrosion is a battery-like process requiring the presence of four elements: anode, cathode, electrolyte, and an electron conduction path. When metal is refined from its original oxide, considerable energy input is required. In situations where all four elements of natural corrosion are present, the metal will tend to revert to its oxide form and lose its structural strength and integrity. This process occurs at the metal surface in contact with an electrolyte. An essential step in the chemical reaction is the loss of an electron into the metal, leaving a positively charged metal atom. This atom would normally combine with a hydroxide molecule and ultimately form an oxide or "rust" product. However, to counteract this reaction, the CP system applies a positive current. Further, by this process of "driving the battery backwards," the criteria requires the metal be further kept at a conservative and assuredly non-corroding energy level. This is determined by measurement of the level of polarization potential.

When CP is first applied, it is possible to measure the amount of increasing polarization of a metallic structure relative to a starting equilibrium native potential. However, the more typical monitoring situation is for existing structures already under CP. In this case, the approach is to temporarily switch off the CP and then, very shortly after a sharp initial potential change, to monitor the polarization potential decay over time. If at least 100 mV of decay is observed, then this is indicative of having achieved acceptable corrosion protection according to criteria. Needless to say, it is essential to then turn the CP system back on again with no adjustments to the settings.

The potential is measured with the aid of a reference electrode (half-cell) and a high input-impedance DC voltmeter; the potential decay data are recorded by a suitable device. If the polarization decay rate is very slow, it can take 4 hours or more to determine if the 100-mV criterion has been met at each test location. Furthermore, for buried structures, polarization readings can be influenced by variations in soil moisture content, diurnal temperature changes, aboveground traffic, the size of the structure (e.g., buried pipelines that run tens of miles), coating system deterioration over time, and so forth. All of these factors make it very time consuming, inconvenient, uneconomical and, in some cases, impractical to perform the criterion-compliance monitoring. Distortions in normal polarization decay can occur over hours or days due to factors such as change in oxygen diffusion, temperature changes, moisture changes in soil, etc. These distortions would be missed if measurements were taken only at the very beginning or end of the depolarization test period. Thus, the corrosion protection industry has had a critical need for a more reliable and faster protocol for monitoring polarization decay to determine the efficacy of CP systems on structures where other criteria cannot be used.

Currently, to measure the effectiveness of CP systems, the impressed current system must be shut off and the structure's polarization monitored for time periods ranging from 4–24 hours or even longer. Given the length of a typical work day, the majority of monitoring must be performed without supervision, thus increasing the probability of error in the measured data.

The goal of this project was to increase the reliability of verifying the realization of criteria compliant CP through the use of rapid and validated prediction methods of long-term polarization potential shifts. This is especially applicable to larger structures where readings are more prone to adverse effects from environmental factors as well as operator error. A concurrent benefit includes time savings. As one example, a large natural gas distribution piping system may have several hundred test stations that each must be tested annually in compliance with federal regulations. The original goal was to obtain a good, accurate, and validated prediction using no more than 15 minutes of polarization decay monitoring data.

To prolong the life of its valuable and mission-critical infrastructure, the Department of Defense (DoD) Corrosion Prevention and Control (CPC) Program funds the Engineer Research and Development Center – Construction Engineering Research Laboratory (ERDC-CERL) to demonstrate and validate corrosion prevention technologies.

For this study, the work consisted of developing a polarization predictive algorithm that is capable of providing a reliable and predictive snapshot of a structure's polarization level in a matter of minutes.

1.2 Objective

The objective of this project was to develop and field-validate a predictive algorithm capable of accurately projecting the longer-term quantitative polarization status of a steel structure equipped with a CP system. A second objective is to create a prototype electronic device to take measurements of polarization levels to aid the development and validation of the predictive algorithm.

1.3 Approach

Prior literature on this subject was first reviewed [4–7]. The project was divided into four main activities. The initial laboratory work was performed by Bushman & Associates (B&A) of Medinah, OH. Measurements were taken for both bare and coated steel samples, using two types of soil with both high- and low-oxygen permeability. The purpose of this work was to become familiar with decay curves for various environments and structure types while standardizing measurement procedures and protocols.

B&A conducted field data collection of multiple representative polarization-decay data sets and developed curve-fitting equations and a predictive algorithm to measure polarization-decay data, along with a preliminary algorithm for field validation testing.

Polarization-decay data were generated from numerous laboratory and field tests. Laboratory tests included test panels immersed in water and buried in 5-gallon buckets. Field test locations included Cleveland, OH; Jacksonville, FL; Indiana, PA; and Fort Leonard Wood, MO. A large number of curve-fitting algorithms were evaluated to determine the best one.

Preliminary performance validation of a prototype measurement and data logging device developed by ERDC-CERL was assessed by using it to gather polarization-decay data on two elevated water tanks at Fort Leonard Wood, MO.

1.4 Metrics

The prediction algorithm was considered successful if the resulting curve-fit matched that of actual data recorded for a structure. An R^2 goodness-of-fit characterization parameter was employed.

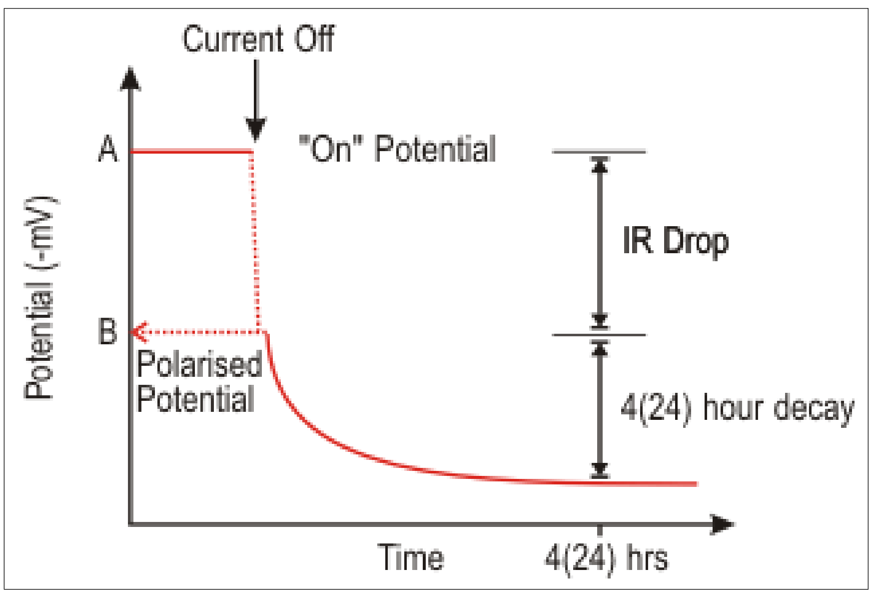
The NACE International standard for measurement of CP was used—TM0497-2012, “Measurement Techniques Related to Criteria for Cathodic Protection on Underground or Submerged Metallic Piping Systems.”

2 Technical Investigation

2.1 Technology overview

Figure 1 shows a typical polarization decay curve. The curve shows a constant "ON" potential followed by a rapid IR potential drop when the current is turned off, followed by a long-term potential decay. Figure 1 uses the convention of showing just the magnitude of the potential readings so as to conceptually emphasize the ongoing decrease in the protective polarization over time. In this report, the equivalent representation showing a "rising" curve (i.e., flipped about the X axis) is also used, where the readings become less negative during polarization decay.

Figure 1. Typical polarization decay curve.



2.2 Polarization-decay measurements

Initial laboratory work was performed by the contractor. Using both low- and high-oxygen permeability soils, polarization decay was studied for bare and well-coated steel samples. Similar samples were also placed in native soil, and polarization-decay data was taken for comparison (See Appendix A).

Polarization-decay data sets for multiple large structures were collected from three different geographical locations (see Appendix B). The representative structures included above-ground water storage tanks, elevated water storage tanks, the steel reinforcement of a power plant cooling tower, and a UST. In all, 17 complete data sets were collected.

2.3 Curve-fit considerations

The purpose of the curve-fit equation was to make it possible to use it in coordination with short-term data measurements in the field to predict with a high degree of confidence that a structure is being provided the correct amount of current that allows it to be fully protected by the ICCP system.

For practical engineering purposes and given the multiple factors involved, no idealized mathematical form of a decay curve was presumed. Instead, a number of likely functions were tested and the associated goodness-of-fit parameter, R^2, was assessed for each. These functions included sinusoidal, exponential, polynomial, hyperbolic decline, Farazdaghi-Harris, and DR-LogProbit [e.g., 8; 9; 10]. Data were assembled by using standard industry practice and engineering judgment, including consideration of key variables such as soil type, structure type and size, structure coating condition and quality (including bare steel), structure location, and climate conditions.

Within any particular data set, each polarization measurement was taken not more than two seconds apart for the initial-period data and at one minute intervals later. The initial period is the period of time when the polarization decay changes noticeably over 60-second intervals. The minimum initial time period was 15 minutes. Three distinct classes of common structures were represented in the polarization data sets: above-ground water storage tanks, steel-reinforced concrete, and steel USTs for fuel. Typical large ferrous structures requiring CP include elevated water storage tanks, natural gas pipelines, water pipelines, and metallic USTs.

The full and complete data sets for curve-fit development were not provided to ERDC-CERL by the contractor. The data sets were used during the laboratory, field comparison, and validation phases. The contractor provided no indication that any peer inspection or review was involved. In addition, the specific predictive algorithm was not provided prior to the contractor's demise and subsequent dissolution of the company.

2.4 Concurrent development of a fieldable hand-held device

As part of this project, a prototype hand-held device was developed and was intended to, ultimately, simplify the process of data taking and analysis. The intent was for the nonspecialist to be able to easily and accurately determine compliance with protective NACE International CP criteria. In the interim, various commercial off-the-shelf (COTS) hardware has been introduced that can be easily adapted to this task. Although there may still be a niche market for the prototype device, provided that the development is completed and that regulatory acceptance of a fitted, rapid assessment method is obtained. The following specifications were determined by this project to be needed for such a handheld device:

- Measurement and storage of DC voltage readings (0–2,000 mV), with resolution of 0.1 mV and accuracy of ±1 mV
- Input impedance range of 10–20 MΩ
- Sampling rate of 1 µs and data-logging rate of one reading per second
- Recording begins after the initial voltage spike of rectifier interruption
- Alternate current (AC) filtering, including rejection of up to 15 volts of alternating current (VAC) at 50/60 Hz
- Digital indicators for power on/off, battery life status, and display of readings acquired in real time
- 16 bit processor
- 512 kB memory
- Universal serial bus (USB) 2.0 or later input/output port for communication with computer running Microsoft Windows 7 or 8 (either 32-bit or 64-bit)
- Ability to receive testing instructions, software and firmware updates from a Windows System 7 or Windows 8 computer via USB 2.0 and also be able to download stored data for analysis
- 1/2 LSb (least significant bit) accuracy (0.366 mV), 0.09375–0.125 LSb (0.0686–0.0915 mV) resolution
- Minimum of 256 data readings
- Unit “ON” indicator, and separate unit data logging LED (light emitting diode) indicator
- Banana plug input receptacle for DC voltage test leads
- Collect data until stopped by pushing a button or at the end of a selected time period (e.g., 600, 900, or 1,200 seconds, or 4 or 24 hours).
- Push-buttons to select the program to be used, to record START and STOP times, and to download data stored in the unit.

- Ability to test multiple locations with each test performed at either 600, 900, or 1,200 seconds, and then download all data sets with correct identifiers for each test.
- Weather-resistant performance with ability to operate over a temperature range of 0°F to 120°F.
- Capability to digitally display selected commands and the last data recorded, on a real-time basis.

2.5 Field experimentation and verification

The goal of the field experimentation was to interrupt CP current to various structures and then measure and record polarization voltages as the cathodic protection of a structure was decaying. Then, using the algorithm described in section 2.3, a polarization-decay curve would be constructed. Finally, the measured polarization voltages would be compared with the constructed decay curve to see if the curve-fit algorithm accurately predicted the long-term polarization decay of the structure. Details and photos of this process for water towers at Fort Leonard Wood, MO, are shown in Appendix C.

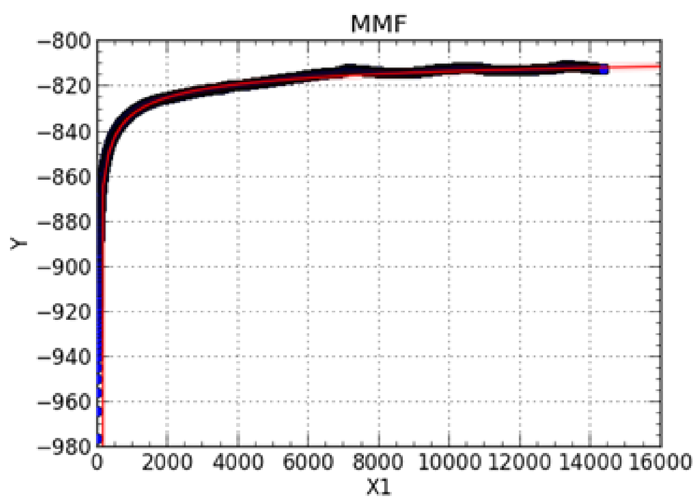
3 Discussion

3.1 Results

3.1.1 Laboratory testing

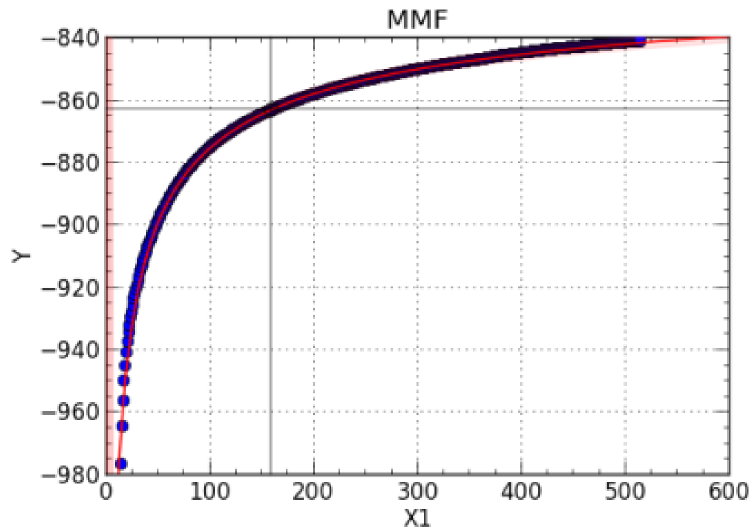
A graphical plot of the potential decay versus time for one bare-steel test panel is shown by the blue line in Figure 2 for slightly more than the first 14,000 seconds (i.e., 3.89 hours). Analysis of the data was performed by using commercially available software. The best graphical fit was obtained with the Morgan-Mercer-Flodin (MMF) model algorithm, as indicated by the red line in Figure 2. All triplicate panels exhibited very similar behavior (see Appendix A). Other mathematical functions were also explored, as described in section 2.3.

Figure 2. Typical polarization decay of bare steel potential vs. time in tap water over 14,000 seconds (curve-fit trend line shown in red).



As shown in Figure 2, the general trend of the polarization decay was a hyperbolic curve (i.e., decreasing rate of decay with time). However, effects such as non-uniform oxygen diffusion in the tap water stagnant solution (open to the atmosphere) appeared to distort the normal polarization decay trend over longer periods as depicted in Figure 2. Coating the panels to minimize waterline effects did not eliminate this behavior. Figure 3 shows that an excellent curve fit was obtained, for example, when data for just the first 500 seconds of polarization decay was used in the trend line analysis.

Figure 3. The first 500 seconds of data from Figure 2 (curve-fit trend line shown in red).



Typical polarization decay and curve-fit analysis in clay soil are shown in Figure 4. The blue line represents the actual decay curve over 9,000 seconds (2.5 hours). The departure from a normal decay curve after the first 1,000 seconds or so is again attributed to effects such as non-uniform oxygen diffusion. The curve-fit trend lines corresponding to data for the first 150, 300 or 600 seconds are also shown. Significant deviation of predicted polarization decay occurs after the first 500 seconds. However, curve-fitting the actual data for just the first 500 seconds exhibits excellent correlation with the B&A model as shown in Figure 5.

This analysis algorithm is intended for rapid application to field-polarization decay data. Within a very short time the results of the curve-fit prediction is obtained and can also be displayed graphically along with the actual data in a standard spreadsheet program. Based on using sufficient preliminary measurement data it will be possible to predict if full CP criteria will be met or not.

Figure 4. Polarization decay of steel potential vs. time in soil over a 9,000 second period. The blue line represents the observed values recorded. The other lines represent predicted curve-fit trends.

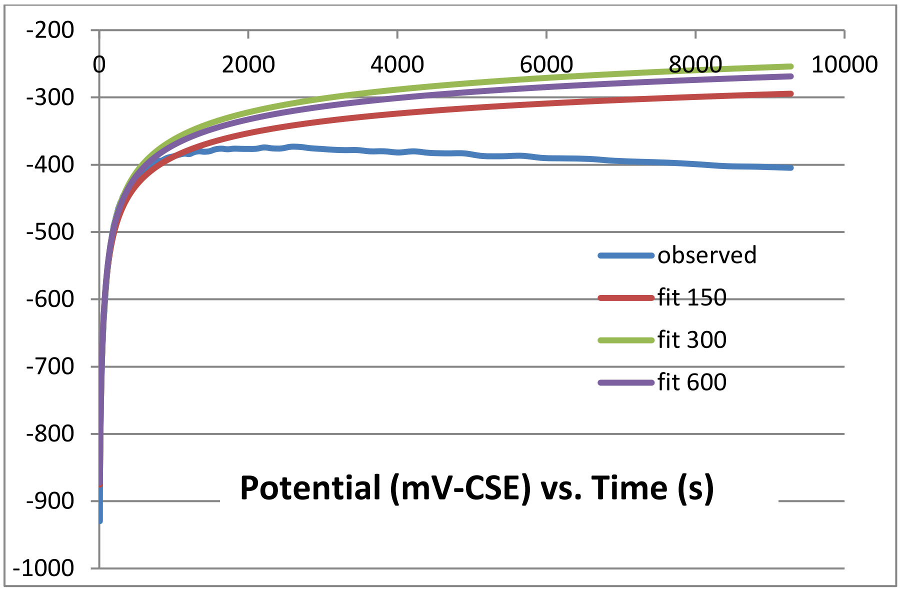
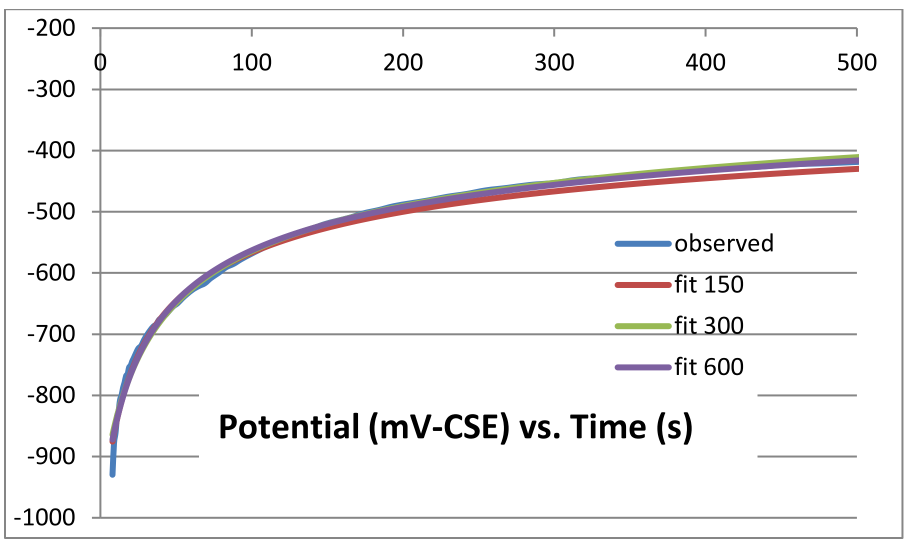


Figure 5. The first 500 seconds of data and curve-fit trend lines from Figure 4.



3.1.2 City of Cleveland field testing

There was excellent agreement between the contractor curve-fit model and the polarization decay data. The curve fit model was compared to 2.76 hours of polarization-decay data measured on a 5-million gallon above-ground water storage tank. The results are shown in Figure 6. The calculated polarization decay values projected for various time periods are summarized in Table 1. The projected data-fit values for 150, 300, 600, and

900 data points (i.e., one per second) are shown. The coefficient of determination, or R^2, is very close to 1.0, indicating exceptional fit between the data points and the contractor model. Also shown for each designated time period is the amount of potential-decay change (i.e. Δ value) with respect to the initial, instant-OFF potential. It should be noted that the predicted values for four hours using the various initial data point fits (i.e., 535–552 mV) are greater than the last measured value of 510 mV which occurred at 2.76 hours. The estimated potential shifts are smaller and hence more conservative than what was measured.

Figure 6. Polarization decay data and curve-fit trend lines for interior of 5-million gallon water storage tank at Cleveland, OH.

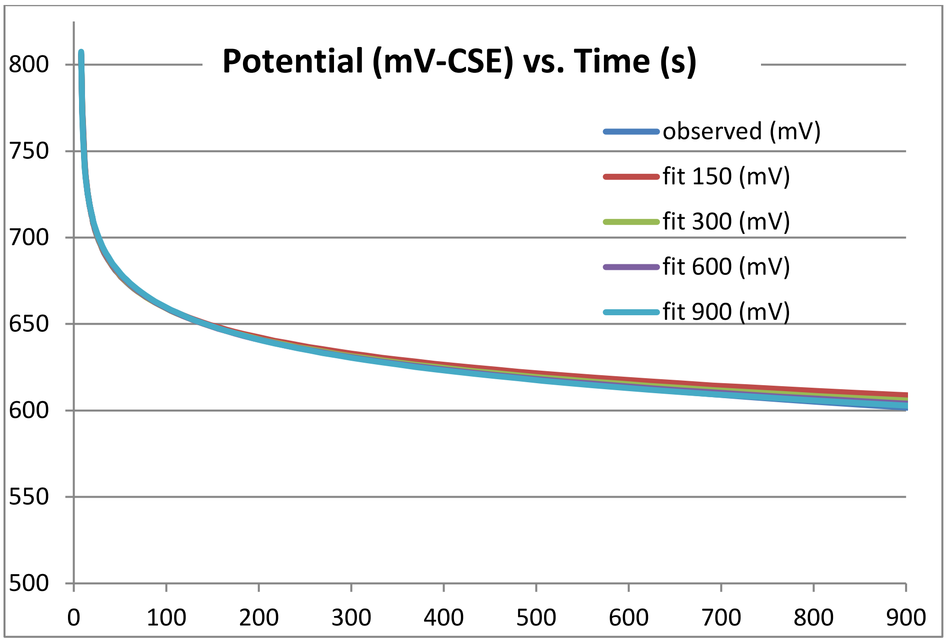


Table 1. Example of calculated polarization decay values for 5-million gallon aboveground water storage tank for extended time periods (up to 1 year) from initial data points (150 to 900) for the curves shown in Figure 6.

Data as MEASURED using Data Logger				
First MEASURED value at 8s (mV)	805.70			
Final MEASURED value at 9929s (mV)	510.30			
Final MEASURED Polarization decay at 9929 (Δ mV)	295.4			
Calculated Projections from B&A Formula	**Fit 150**	**Fit 300**	**Fit 600**	**Fit 900**
4-Hour Calculated Value (mV) (Polarization decay Δ mV)	551.77 (253.93)	544.00 (261.70)	539.1 (266.6)	535.09 (270.61)
12-Hour Calculated Value (mV) (Polarization decay Δ mV)	529.93 (275.77)	520.11 (285.59)	513.82 (291.88)	508.57 (297.13)
24-Hour Calculated Value (mV) (Polarization decay Δ mV)	516.26 (289.44)	505.14 (300.56)	497.94 (307.76)	491.89 (313.81)

Calculated Projections from B&A Formula	Fit 150	Fit 300	Fit 600	Fit 900
48-Hour Calculated Value (mV) (Polarization decay Δ mV)	502.67 (303.03)	490.22 (315.48)	482.11 (323.59)	475.23 (330.47)
One-Year Calculated Value (mV) (Polarization decay Δ mV)	402.07 (403.63)	379.25 (426.45)	363.98 (436.72)	350.67 (455.03)
Coefficient of Determination, R^2 (fitted range)	0.99972	0.99963	0.99964	0.99928
Coefficient of Determination (150 points)	0.99972	0.9995	0.99911	0.99816
Coefficient of Determination (300 points)	0.99854	0.99963	0.99939	0.99886
Coefficient of Determination (600 points)	0.99121	0.99869	0.99964	0.99924
Coefficient of Determination (900 points)	0.97673	0.99428	0.99847	0.99928
Coefficient of Determination (full observed range)	0.02903	0.31785	0.46978	0.57692

3.1.3 Florida data testing

In all these cases, there was excellent fit between the data and the contractor model. An example of the polarization decay measurements taken at 5-minute intervals and the contractor model curve-fits is shown graphically in Figure 7. The calculated polarization decay values projected for various time periods are summarized in Table 2. Shown are values from the predictive algorithm for various longer time intervals based on the four cases of using the initial 150, 300, 600, and 900 data points. Again, very good polarization decay correlation is indicated. It should be noted that the test results from all of the polarization decay projections are only considered reliable for 4–24-hour projects. Projections for longer time periods are considered not acceptable unless substantially longer decay data is provided and analyzed.

Figure 7. Polarization decay data and curve-fit trend lines for steel-reinforced concrete power-plant cooling tower at Jacksonville, FL.

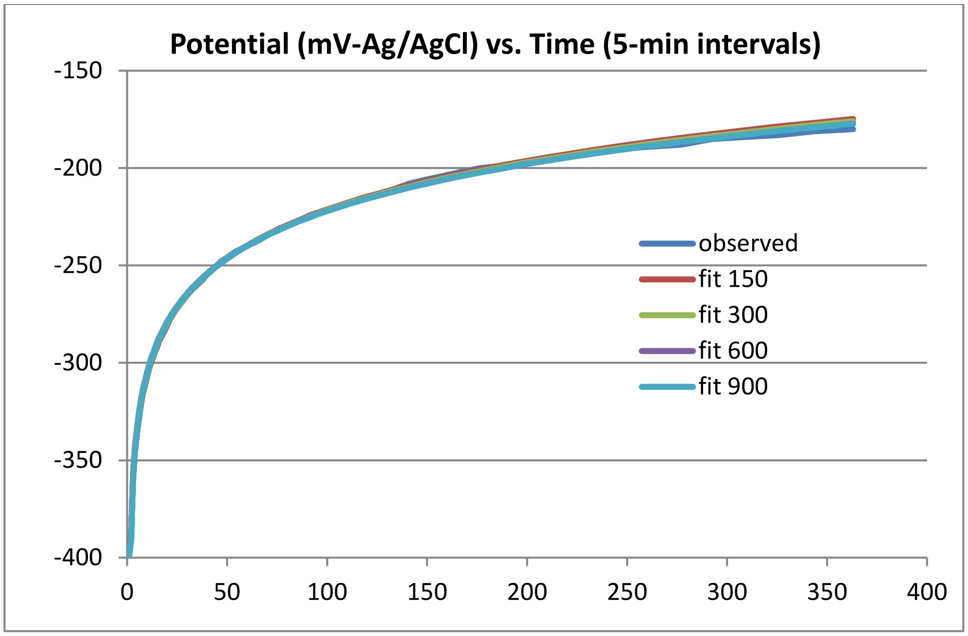


Table 2. Calculated polarization-decay values for steel-reinforced concrete power-plant cooling tower from initial data points (150 to 900) for the curves shown in Figure 7.

Data as MEASURED using Data Logger				
First measured value at 1s	-399.00 mV			
Final measured value at 371 s	-180.00 mV			
Final MEASURED Polarization decay at 371 s (Δ mV)	219			
Calculated Projections from B&A Formula	**Fit 150**	**Fit 300**	**Fit 600**	**Fit 900**
4-Hour Calculated Value (Polarization decay Δ mV)	-42.93 mV (356.07)	-46.33 mV (352.67)	-50.30 mV (348.70)	-50.30 mV (348.30)
12-Hour Calculated Value (Polarization decay Δ mV)	-3.65 mV (395.35)	-7.72 mV (391.28)	-12.51 mV (386.49)	-12.51 mV (386.49)
24-Hour Calculated Value (Polarization decay Δ mV)	21.13 mV (420.13)	16.63 mV (415.63)	11.33 mV (410.33)	11.33 mV (410.33)
48-Hour Calculated Value (Polarization decay Δ mV)	45.90 mV (444.90)	40.97 mV (439.97)	35.16 mV (434.16)	35.16 mV (434.16)
One-Year Calculated Value (Polarization decay Δ mV)	231.87 mV (630.87)	223.72 mV (622.72)	214.04 mV (613.04)	214.04 mV (613.04)
Coefficient of Determination, R^2 (fitted range)	0.99977	0.99939	0.9984	0.9984
Coefficient of Determination (150 points)	0.99977	0.99961	0.99902	0.99902
Coefficient of Determination (300 points)	0.99901	0.99939	0.99893	0.99893
Coefficient of Determination (600 points)	0.99617	0.99779	0.9984	0.9984

Calculated Projections from B&A Formula	Fit 150	Fit 300	Fit 600	Fit 900
Coefficient of Determination (900 points)	0.99617	0.99779	0.9984	0.9984
Coefficient of Determination (full observed range)	0.99617	0.99779	0.9984	0.9984

In Table 2, it should be noted that the test results from all of the polarization decay projections are only considered reliable for 4–24 hours. Projections for longer time periods are considered unacceptable unless substantially longer decay data is provided and analyzed.

3.1.4 Indiana, PA, data testing

Typical plots are shown in Figure 8 where the curve fit model was compared to 6.37 of polarization decay data. All of the data analyses validated the contractor's curve-fit model. An example of the calculated polarization decay values for extended times from the initial data points are shown in Table 3. It is apparent that the coefficients of determination (R^2 values) indicate nearly perfect fit of data to the contractor model, with differences of only ~15 mV between the projected 4-hour and 24-hour values.

Figure 8. Polarization decay data and curve-fit trend lines for exterior of a 50,000-gallon underground fuel storage tank at Indiana, PA.

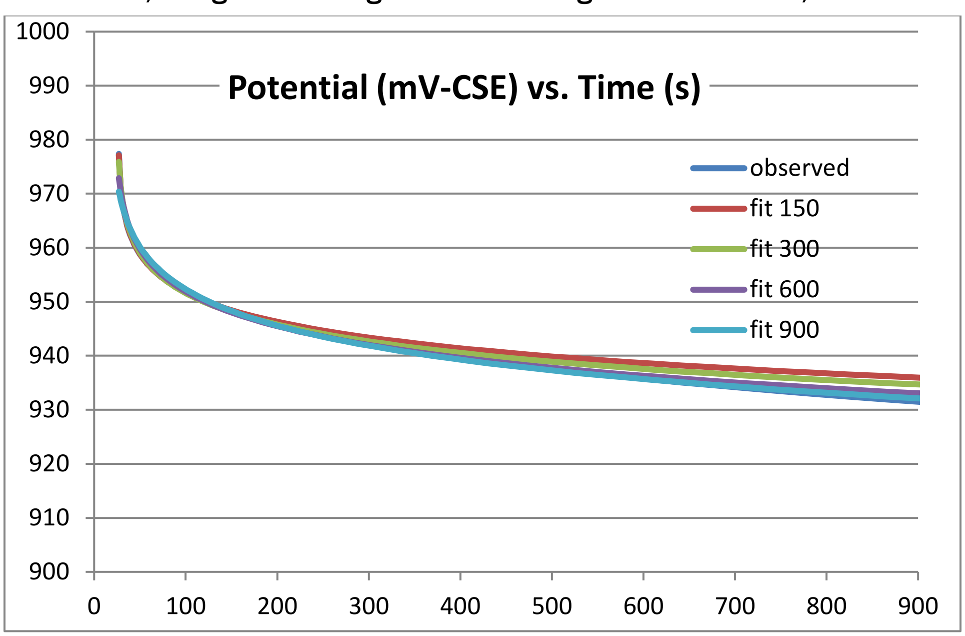


Table 3. Example of calculated polarization decay values for 50,000-gallon fuel UST for extended time periods (up to 1 year) from initial data points (150 to 900) for the curves shown in Figure 8.

First measured value at 27s	977.37 mV			
Final measured value at 22927 s	877.20 mV			
Final **MEASURED** Polarization decay at 22927s (Δ mV)	100.17			
Calculated Projections from B&A Formula	**Fit 150**	**Fit 300**	**Fit 600**	**Fit 900**
4-Hour Calculated Value (Polarization decay Δ mV)	918.08 mV (59.29)	915.42 mV (61.95)	911.15 mV (66.22)	907.96 mV (69.41)
12-Hour Calculated Value (Polarization decay Δ mV)	911.07 mV (66.30)	907.86 mV (69.51)	902.53 mV (74.84)	898.41 mV (78.97)
24-Hour Calculated Value (Polarization decay Δ mV)	906.65 mV (70.72)	903.10 mV (74.27)	897.09 mV (80.28)	892.36 mV (85.01)
48-Hour Calculated Value (Polarization decay Δ mV)	902.23 mV (75.14)	898.34 mV (79.03)	891.65 mV (85.72)	886.31 mV (91.27)
One-Year Calculated Value (Polarization decay Δ mV)	869.05 mV	862.56 mV	850.73 mV	840.70 mV
Coefficient of Determination (fitted range)	0.99956	0.99824	0.99619	0.99522
Coefficient of Determination (150 points)	0.99956	0.99714	0.98776	0.97235
Coefficient of Determination (300 points)	0.99241	0.99824	0.99296	0.98615
Coefficient of Determination (600 points)	0.94758	0.98291	0.99619	0.99324
Coefficient of Determination (900 points)	0.88226	0.94844	0.98979	0.99522

3.1.5 Fort Leonard Wood preliminary field testing

Field testing was performed jointly by ERDC-CERL and the contractor on three ICCP systems operating at Fort Leonard Wood, MO. Details of the procedure are provided in Appendix C. For comparison purposes, polarization-decay data sets were concurrently measured from the same instantaneous input using two separate recording systems. Not all data sets were recorded in duplicate. The three systems tested were:

- Indiana Avenue, 500,000-gallon elevated water storage tank:
  - A first scan, with readings taken every second for 9,990 readings
  - A second scan taken simultaneously, with readings taken every 10 seconds for 20 hours total
  - A third scan with readings taken every second for 127 readings
- Indiana Avenue, 2,250,000-gallon above-ground water storage tank:

    - A scan with readings taken every second for 9,990 readings
- Airfield, 500,000-gallon elevated water storage tank:
    - A scan with readings taken every second for 9,990 readings

The field validation analysis of implementing the contractor curve-fit algorithm showed good results for the airfield's elevated water storage tank. The R^2 goodness-of-fit parameters using the first 150, 300, 600, and 900 readings (i.e., 2.5–15 minutes) were excellent (see Appendix C).

3.2 Lessons learned

This promising technology was shown to be effective at the proof of principle level. The ability to quickly and accurately predict the achievement of the 100 mV criterion was demonstrated to take only a fraction of the time that is now required. However, from a conservative engineering perspective, further work is required prior to acceptance and widespread use of this technology. Based on the work documented here, the subsequent development path should include:

- further openly documented algorithm development and testing for a wider set of representative field conditions and structures;
- wider openly documented validation testing for multiple geographical locations and structures; and
- development and implementation of a detailed criteria-acceptance plan involving both long-term participation on the NACE International committee responsible for Standard Test Method (TM) TM0497 and a multiparticipant round robin test involving peer review.

Another lesson learned for similar future development efforts is that the contract scope of work should be more explicit about government ownership of the technology developed, while also requiring multiple intermediate deliverables. In future validation of the technology on multiple types of structures, ideally at least one example of each type of structure should be tested at multiple locations.

4 Economic Summary

The total project costs were $280,000. A rough breakdown of the project expenses is shown in Table 4.

Table 4. Breakdown of project costs.

Description	Amount, $K
Labor	153
Materials	24
Contracts	63
Travel	20
Reporting	20
Air Force and Navy participation	0
Total	**280**

The contract expenses for this project are detailed in Table 5.

Table 5. Breakdown of project contract costs.

Item	Description	Amount, $K
1	Labor for project management and execution	44.5
2	Travel for project management	12.0
3	Cost for materials	2.6
4	Shipping costs	0.5
5	Cost for installation	3.0
	Total	**62.6**

4.1 Costs and assumptions

Total direct costs were $140K, with $140K in matching funds from Fort Leonard Wood. Thus, the investment required was $280K. The direct costs included sums for labor, contracts, materials, travel, and written reports. These costs were shared between OSD and Fort Leonard Wood.

Because this demonstration evaluated a novel technology for rapidly confirming structure polarization or depolarization without directly observing the entire process onsite, its costs and benefits are compared with the current industry practice. A 30-year cost analysis was performed for six 500,000-gallon water towers that compares current industry practice costs with estimated costs for the evaluated technology. Depending on the age of a structure being tested, typical annual maintenance inspection costs are estimated at $1,000 per tower, totaling $6,000 annually. This annual inspection will be unchanged by the introduction of the evaluated technology. Similarly, repainting the exterior of the structure must be done every 10 years at a cost of approximately $80,000 per tower, totaling $400K every 10 years. By replacing a tank every 10 years in the baseline case, and every 20 years in the new system case, the inspections and interior and exterior painting of the tank being replaced will not be required in those ears. The degradation of the exterior of the structure is unaltered by interior CP, so the introduction of the evaluated technology will not alter this cost. Primary differences in cost are outlined in the two alternative scenarios below.

The basis for comparison of this novel technology is that the current criteria verification method involves long-term monitoring over as much as 24 hours. With the new technology, that monitoring can be accomplished in 1 hour or less. This shorter monitoring time eliminates the introduction of environmental error and allows for a more accurate determination of the polarization decay. This, in turn, allows for more effective cathodic protection of the structure.

Alternative 1 (Baseline Scenario). The current verification method takes 8 hours per test, on average, with five tests required per water tower. These tests need to be performed annually. Some will take more time and others will take less time. This also assumes periodic monitoring checks versus being present at the test station during the entire time, as well as occasionally having to start over. The fully burdened cost per hour is $230 for a contractor. The contractor rate includes costs of travel, data analysis, reporting, etc. For six water towers, this amounts to $55.2K per year for monitoring.

The interior of a water tower, as protected by current cathodic protection techniques, needs to be repainted approximately once every 10 years. This will cost $120K per water tower, amounting to $600K every 10 years.

With current techniques, a failure or major repair in a water tower can be expected to occur approximately every 60 years. For six water towers, this amounts to a major repair or replacement of a single tower once every 10 years for $2.6M. This amount also accounts for the disposal/replacement costs of a single water tower and associated failure damages.

Alternative 2 (Demonstrated Technology). The new technology requires 1 hour per test—30 minutes of monitoring and 30 minutes of analysis and record keeping. Each water tower requires five separate tests, amounting to 30 tests for the six water towers. For a contractor at $230 per hour (including travel, analysis, reporting, etc.), this totals to $6.9K per year for all six water towers.

Due to increased monitoring accuracy, the CP system will better protect the interior of the water tower. This improved monitoring reduces the required interior painting to once every 15 years at a cost of $720K.

The technology developed in this work, once fully accepted by regulatory agencies and implemented, is more reliable and provides more accurate results. Compared to the current method, this increased reliability results in preventing the premature failure of a major piece of infrastructure. This increased accuracy and reliability leads to an increase in the estimated lifetime of a water tower to 120 years. For six water towers, this leads to a major failure or replacement of a single tower once every 20 years for $2.6M. This amount also accounts for the disposal/replacement costs of a single water tower and associated failure damages.

4.2 Projected return on investment (ROI)

The original ROI estimate for this project was 10.80, or a return of 1080% and can be found in the project management plan (PMP). The final ROI is 8.55, or a return of 855% over 30 years. The calculation is based on a required CPC project investment of $280,000. A summary of the analysis is show in Table 6. Both of the ROI calculations followed Office of Management and Budget (OMB) Circular A-94. The difference between the initial and final ROI is attributed to a shift in comparison analysis from a pipeline to an elevated water storage system. Pipelines have much higher maintenance and replacement costs associated with failure, and a more accurate monitoring system that led to a reduced failure rate would have a greater monetary impact.

Table 6. Return on investment spreadsheet.

Return on Investment Calculation

Investment Required			280
Return on Investment Ratio	8.55	Percent	855%
Net Present Value of Costs and Benefits/Savings	1,597	3,992	2,394

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	61.2		12.9		12.1	57.2	45.1
2	61.2		12.9		11.3	53.5	42.2
3	61.2		12.9		10.5	50.0	39.4
4	61.2		12.9		9.8	46.7	36.8
5	61.2		12.9		9.2	43.6	34.4
6	61.2		12.9		8.6	40.8	32.2
7	61.2		12.9		8.0	38.1	30.1
8	61.2		12.9		7.5	35.6	28.1
9	61.2		12.9		7.0	33.3	26.3
10	3,660.2		492.9		250.5	1,860.5	1,609.9
11	61.2		12.9		6.1	29.1	22.9
12	61.2		12.9		5.7	27.2	21.4
13	61.2		12.9		5.4	25.4	20.0
14	61.2		12.9		5.0	23.7	18.7
15	61.2		732.9		265.6	22.2	-243.4
16	61.2		12.9		4.4	20.7	16.4
17	61.2		12.9		4.1	19.4	15.3
18	61.2		12.9		3.8	18.1	14.3
19	61.2		12.9		3.6	16.9	13.4
20	3,660.2		3,010.8		778.0	945.8	167.8
21	61.2		12.9		3.1	14.8	11.7
22	61.2		12.9		2.9	13.8	10.9
23	61.2		12.9		2.7	12.9	10.2
24	61.2		12.9		2.5	12.1	9.5
25	61.2		12.9		2.4	11.3	8.9
26	61.2		12.9		2.2	10.5	8.3
27	61.2		12.9		2.1	9.8	7.8
28	61.2		12.9		1.9	9.2	7.3
29	61.2		12.9		1.8	8.6	6.8
30	3,660.2		1,212.9		159.4	481.0	321.6

5 Conclusions and Recommendations

5.1 Conclusions

A technology able to quickly and accurately predict the future meeting of CP criteria was demonstrated on two types of large structures at one geographical location. The predictive curve-fit algorithm development used 17 field data sets taken from four different structures, as well as small-scale laboratory input. No data from a buried metallic piping network was included. Validation documentation was provided from one of the two types of structures tested at Fort Leonard Wood. Nonetheless, the results from this effort show good potential and future promise, provided that further development and pursuit of criteria acceptance is continued.

An accurate and validated prediction algorithm will allow for significant time savings every time it is used on large metallic structures to verify the achievement of fully protective CP that meets NACE International criteria. In addition, improved accuracy and reliability will be derived from the fact that during the shorter measurement interval, there will be less chance of broad weather and environmental changes that can adversely impact potential measurement readings.

Further developmental testing should include direct comparisons, with no other factor variations, of long term polarization decay data sets with and without environmental disruptions (e.g., variations in oxygen diffusion, soil moisture content, temperature, vehicular soil compaction). Only in this way can the predicted long term values be shown to be equivalent to the current accepted method without environmental interruption. The documentation of the effects of environmental disruption and how long term readings differ from predictions would also aid validation and hence widespread acceptance.

5.2 Recommendations

5.2.1 Applicability

Thus far, the potential applicability of this technology has been demonstrated. It should be especially applicable to large structures that require long time intervals to polarize or depolarize. Once fully developed, validated, and accepted by NACE International (as discussed below under "Implementation"), this technology should improve the reliability of checking the achievement of a 100 mV shift to meet the criterion for full CP.

5.2.2 Implementation

Once this technology is fully developed and validated, the results will be used to develop DoD facilities engineering guidance (e.g., Unified Facilities Guide Specifications [UFGS] and Unified Facilities Criteria [UFC]) for taking fast and reliable polarization decay measurements. Lessons learned will be noted and included in the associated DoD engineering guidance (e.g., UFGSs and UFCs) as well as in Assistant Chief of Staff for Installation Management (ACSIM) guidance published under its Installation Design Standards process. Specifically, for faster, more reliable monitoring of impressed current systems, these three facilities engineering documents should be revised:

- UFGS 26 42 22.00 20, “Cathodic Protection System for Steel Water Tanks”– paragraph 3.4, “Criteria for Cathodic Protection.”
- UFGS 26 42 17.00 10, “Cathodic Protection System (Impressed Current)” – paragraphs 3.1, “Criteria of Protection” and 3.6.4, “Electrode Potential Measurements.”
- UFGS 26 42 19.10, “Cathodic Protection System (Impressed Current) for Lock Miter Gates” – paragraphs 1.3.2, “Performance Requirements” and especially 1.3.2.2, “Second Criterion.”

When this technology application has been successfully demonstrated, validated, and implemented by DoD, it will be suitable for consideration to incorporate into NACE TM0497-2012 [3] and NACE SP0169-2013 [2].

References

1. Jackson, Joshua E. 2016. "Cost of Corrosion Annually in the US Over $1.1 Trillion in 2016." Houston, TX: G2MT Labs. Accessed http://www.g2mtlabs.com/corrosion/cost-of-corrosion/.

2. NACE SP0169-2013. 2013. "Corrosion Control of Underground or Submerged Metallic Piping Systems." Houston, TX: NACE International.

3. NACE TM0497-2012. 2012. "Measurement Techniques Related to Criteria for Cathodic Protection on Underground or Submerged Metallic Piping Systems." Houston, TX: NACE International.

4. Schwerdtfeger, W. J. 1959. "Current and Potential Relations for the Cathodic Protection of Steel in a High Resistivity Environment." *Journal of Research of the National Bureau of Standards – Section C: Engineering and Instrumentation* 63C (1), July-September.

5. Yan, J.-F., N. R. Pakalapati, T. V. Nguyen, R. E. White, and R. B. Griffin. 1992. "Mathematical Modeling of Cathodic Protection Using the Boundary Element Method with a Nonlinear Polarization Curve." *Journal of the Electrochemical Society* 139(7).

6. Devereux, Owen F. 1979. "Polarization Curve-Fitting by Computer Modeling." *Corrosion* 35 (3): 125-129.

7. Alfaro, Marco. 2014. "Modeling of Polarization Curves Not Exhibiting a Tafel Region Using Excel Spreadsheets." *Alexandria Engineering Journal* Vol. 53:977–983.

8. Kvam, Paul H. and Brani Vidakovic. 2007. *Nonparametric Statistics with Applications to Science and Engineering*. Hoboken, NJ: John Wiley & Sons, Inc.

9. Zielesny, Achim. 2011. *From Curve Fitting to Machine Learning: An Illustrative Guide to Scientific Data Analysis and Computational Intelligence*. Vol. 18 in Intelligent Systems Reference Library series. Berlin, Germany: Springer Berlin Heidelberg. doi: 10.1007/978-3-642-21280-2.

10. Arlinghaus, Sandra. 1994. *Practical Handbook of Curve Fitting*. Boca Raton, FL: CRC Press, Taylor & Francis Group.

Appendix A: Laboratory Measurements

More than 40 polarization-decay tests were performed in the laboratory to check the experimental setup, procedure, and data-collection system. A portion of a typical data set is shown in Table A1 and, identically, is shown in graphical form in Figure A1. Table A1 contains the first 100 data points of a test lasting four hours. The sampling rate was one reading per second and the CP current applied was 10 mA per square foot. Three identical 4 x 12 in. bare steel plates were used as samples, with 10 in. being submerged in the water.

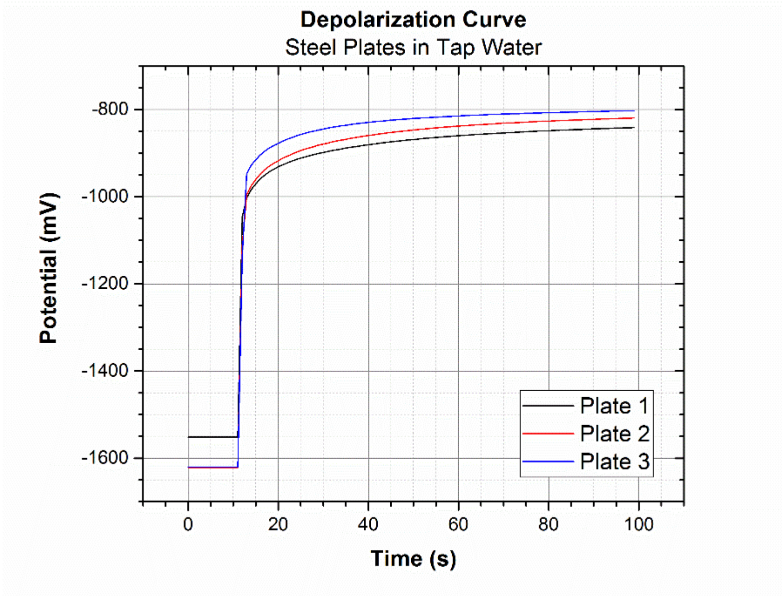
Table A1. Example partial data set for triplicate measurements on bare steel plates in tap water.

Time (s)	Plate 1 Potential (mV)	Plate 2 Potential (mV)	Plate 3 Potential (mV)
0	-1551.328	-1621.178	-1620.367
1	-1551.353	-1621.207	-1620.41
2	-1551.38	-1621.198	-1620.407
3	-1551.38	-1621.212	-1620.425
4	-1551.409	-1621.229	-1620.433
5	-1551.418	-1621.25	-1620.451
6	-1551.424	-1621.26	-1620.475
7	-1551.44	-1621.272	-1620.487
8	-1551.463	-1621.27	-1620.481
9	-1551.499	-1621.283	-1620.491
10	-1551.545	-1621.281	-1620.475
11	-1551.566	-1621.292	-1620.523
12	-1046.177	-1112.313	-1138.125
13	-1003.034	-995.591	-947.636
14	-983.889	-974.635	-927.729
15	-970.591	-960.061	-914.699
16	-959.337	-948.271	-904.272
17	-950.575	-938.27	-895.805
18	-943.294	-930.295	-888.442
19	-937.141	-923.532	-882.614
20	-931.523	-917.502	-877.366
21	-926.717	-911.714	-872.614
22	-922.418	-906.81	-868.138
23	-918.411	-902.308	-864.277
24	-914.744	-898.095	-860.736
25	-911.482	-894.222	-857.437
26	-908.471	-890.75	-854.402
27	-905.672	-887.635	-851.784

Time (s)	Plate 1 Potential (mV)	Plate 2 Potential (mV)	Plate 3 Potential (mV)
28	-903.096	-884.645	-849.312
29	-900.657	-881.766	-846.926
30	-898.362	-879.146	-844.707
31	-896.112	-876.715	-842.722
32	-894.103	-874.308	-840.88
33	-892.186	-872.155	-839.062
34	-890.379	-870.133	-837.483
35	-888.592	-868.243	-835.996
36	-886.883	-866.23	-834.511
37	-885.252	-864.462	-833.113
38	-883.727	-862.823	-831.868
39	-882.199	-861.159	-830.656
40	-880.741	-859.538	-829.471
41	-879.373	-858.071	-828.38
42	-878.061	-856.69	-827.373
43	-876.71	-855.263	-826.385
44	-875.507	-853.943	-825.454
45	-874.307	-852.666	-824.525
46	-873.115	-851.432	-823.667
47	-871.949	-850.22	-822.847
48	-870.854	-849.041	-822.046
49	-869.815	-847.967	-821.3
50	-868.801	-846.931	-820.589
51	-867.783	-845.878	-819.894
52	-866.818	-844.856	-819.216
53	-865.899	-843.919	-818.58
54	-865.005	-843.015	-817.975
55	-864.103	-842.094	-817.38
56	-863.242	-841.187	-816.786
57	-862.431	-840.362	-816.233
58	-861.638	-839.565	-815.707
59	-860.848	-838.763	-815.196
60	-860.085	-837.968	-814.683
61	-859.363	-837.241	-814.199
62	-858.66	-836.536	-813.74
63	-857.945	-835.816	-813.284
64	-857.278	-835.122	-812.835
65	-856.623	-834.462	-812.396
66	-855.959	-833.827	-811.988
67	-855.347	-833.179	-811.588
68	-854.742	-832.572	-811.177
69	-854.145	-831.984	-810.797

Time (s)	Plate 1 Potential (mV)	Plate 2 Potential (mV)	Plate 3 Potential (mV)
70	-853.574	-831.421	-810.43
71	-853.024	-830.85	-810.082
72	-852.524	-830.363	-809.746
73	-851.991	-829.804	-809.388
74	-851.423	-829.253	-809.046
75	-850.914	-828.749	-808.703
76	-850.406	-828.255	-808.382
77	-849.905	-827.765	-808.069
78	-849.444	-827.297	-807.772
79	-848.992	-826.846	-807.47
80	-848.508	-826.393	-807.172
81	-848.074	-825.958	-806.895
82	-847.652	-825.535	-806.619
83	-847.221	-825.108	-806.341
84	-846.801	-824.699	-806.07
85	-846.383	-824.306	-805.81
86	-845.98	-823.897	-805.554
87	-845.592	-823.518	-805.301
88	-845.205	-823.14	-805.047
89	-844.807	-822.774	-804.808
90	-844.438	-822.401	-804.568
91	-844.085	-822.058	-804.341
92	-843.729	-821.711	-804.108
93	-843.366	-821.368	-803.88
94	-843.021	-821.039	-803.662
95	-842.682	-820.703	-803.452
96	-842.342	-820.38	-803.225
97	-842.021	-820.069	-803.021
98	-841.694	-819.774	-802.822
99	-841.376	-819.457	-802.619

Figure A1. Depolarization curve of three steel plates in tap water.



The first set of indoor laboratory experiments was performed using triplicate bare carbon steel test panels measuring 4 x 12 x 1/4 in. The specimens were immersed in tap water in a 5-gallon aquarium-type glass tank. An ICCP setup was applied to the panels. The electrical potential of each panel with respect to a standard copper/copper sulfate reference electrode was measured using a commercial recording voltmeter. Measurements were recorded using a commercial high-resolution data logger. Overall and close-up views of the test setup are shown in Figure A2 through Figure A6.

To test polarization decay for this setup and the two described below, the CP current was interrupted after 24–72 hours, and polarization decay was monitored and recorded by the data logger at a rate of one data point per second.

Figure A2. Overall laboratory setup for polarization-decay testing.

Figure A3. Tank containing triplicate steel test panels and reference electrode.

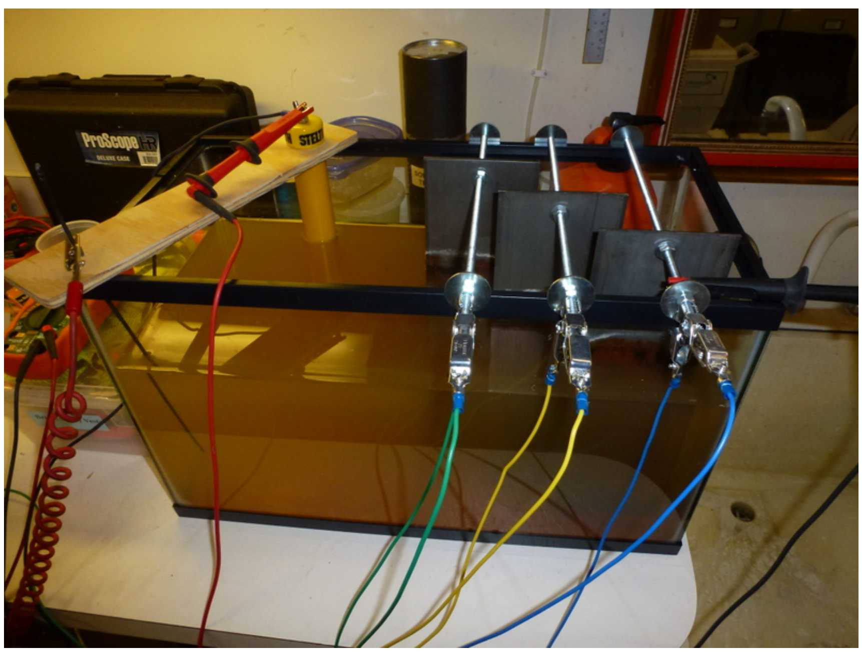


Figure A4. High-resolution data logger and toggle switches for interrupting CP current.

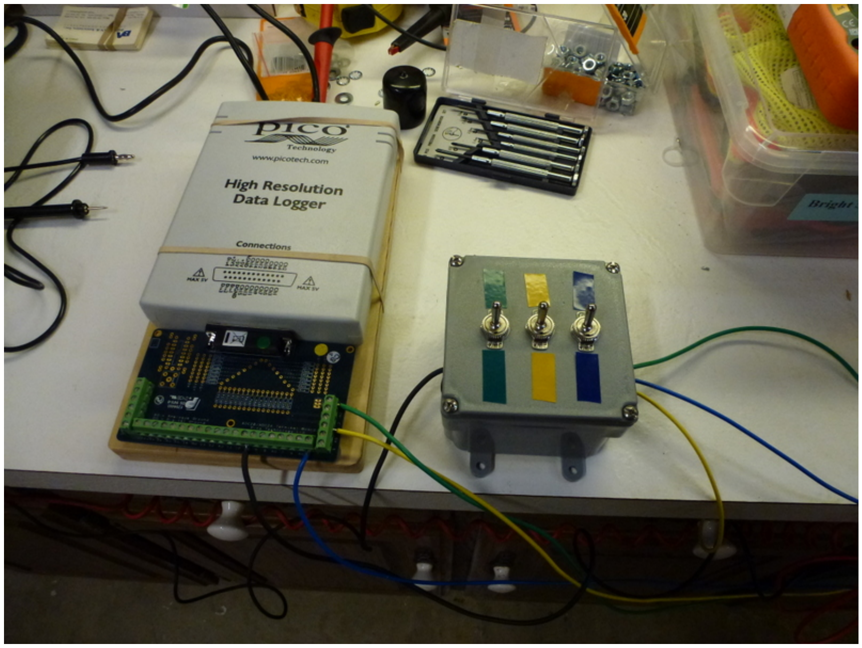


Figure A5. Commercial recording voltage meter connected to switch-box.

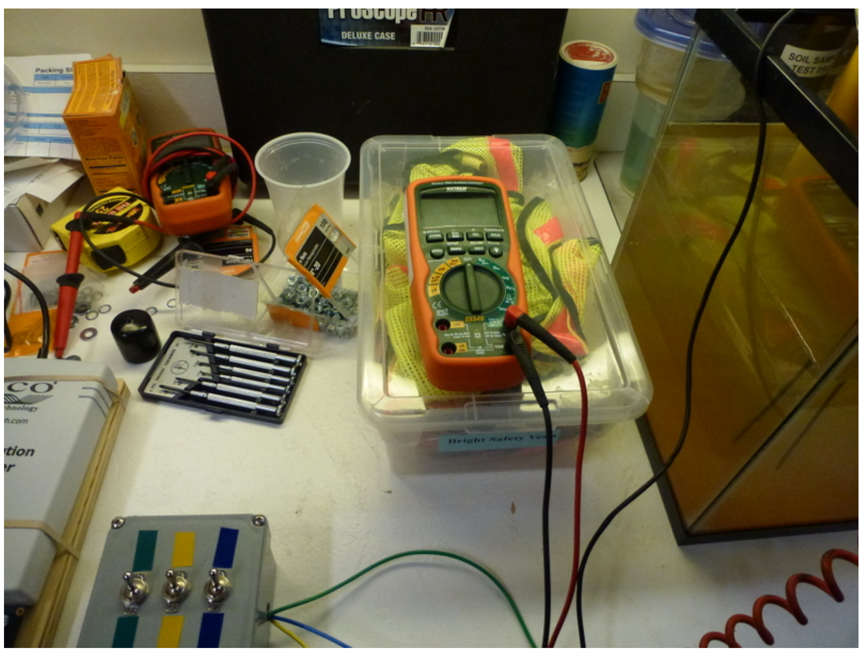
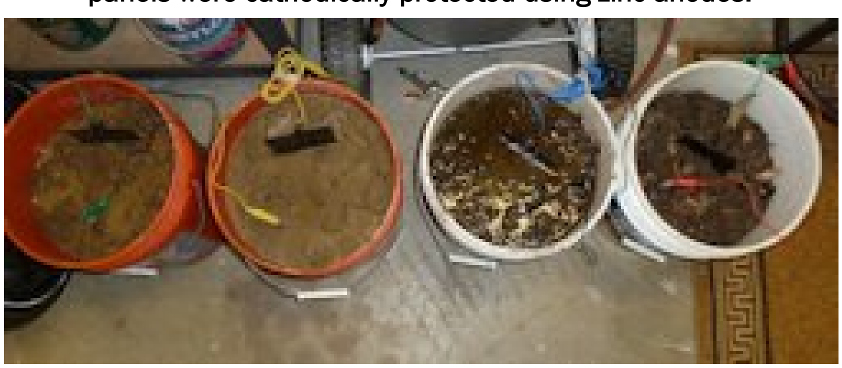


Figure A6. Direct current (DC) power supply for CP setup and laptop computer for data analysis and graphical plots.

A second set of indoor laboratory tests was conducted by using coated steel panels partially buried in four 5-gallon buckets containing two types of soil (Figure A7): (1) dense clay with poor oxygen permeability (orange buckets) and (2) sandy loam that had high oxygen permeability(white buckets). These panels were cathodically protected using magnesium or zinc sacrificial anodes (i.e., galvanic CP). It should be noted that the source of positive CP current directed at a structure to be protected does not matter. Equivalent current densities and polarization potentials can be achieved by either impressed current or galvanic methods. The usual determining selection factor for application is relative cost.

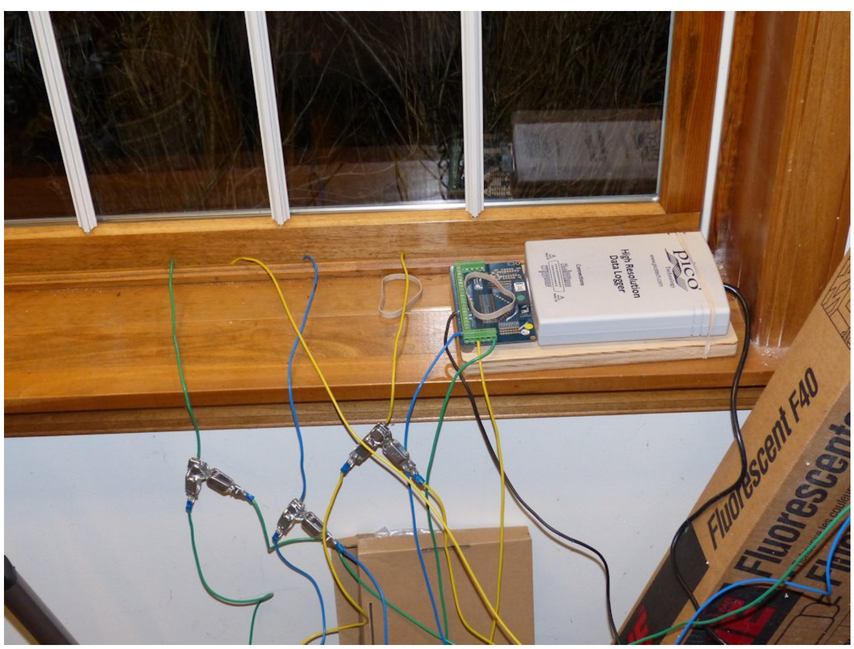
Figure A7. Steel test panels embedded in wet soil in 5-gallon plastic buckets. Test panels were cathodically protected using zinc anodes.



A third set of triplicate panels was used for outdoor laboratory testing, buried in native soil outside the laboratory of Bushman and Associates in Medina, OH (see Figures A8 and A9). ICCP was applied to these outdoor specimens.

Figure A8. Outdoor soil test setup.

Figure A9. Wiring and data-logger for outdoor soil testing.



Appendix B: Field Data Collection

Polarization-decay measurements were made on full-scale steel structures at three different U.S. locations: Cleveland, OH; Jacksonville, FL; and Indiana, PA (near Pittsburgh). In all cases the measurement process included the monitoring and recording of sequential instantaneous polarization readings after the interruption of the rectifier. All readings were taken with a digital volt meter and with respect to a standard $Cu/CuSO_4$ reference half-cell. Upon completion of taking readings, the rectifier was reenergized.

Measurements were taken from two City of Cleveland potable water storage tanks. One was an elevated structure with a capacity of 1-million gallons (Figure B1 and Figure B2); the other was an above-ground tank with a capacity of 5-million gallons (Figure B3 and Figure B4). Both tanks were well coated on the interior and were protected by operating ICCP systems.

Figure B1. Elevated 1-million gallon tank.

Figure B2. Polarization-decay measurements in progress at the CP rectifier for the 1-million gallon elevated water storage tank.

Figure B3. Above-ground 5-million gallon water storage tank.

Figure B4. Polarization decay measurements in progress at the rectifier for the 5-million gallon water storage tank.

At a power plant in Jacksonville, FL, polarization-decay measurements were taken by the CPC project contractor from several locations on a steel-reinforced concrete cooling tower. These data were analyzed with six additional sets collected by an onsite contractor for the power plant.

At Indiana, PA, polarization-decay measurements were taken at eight test-station points for four 50,000-gallon capacity underground steel fuel storage tanks. Each steel tank was coated and protected by an impressed current CP system. The test setup is shown in Figure B5 and Figure B6.

Figure B5. Test setup for polarization decay measurements on four underground fuel storage tanks (each 50-million gallon capacity).

Figure B6. Close-up view of meters and leads shown in Figure B5.

Appendix C: Preliminary Field Validation Testing

Overall views of these tanks and the polarization-decay test setups are shown in Figures C1 through C8. After successfully recording and downloading, all data were submitted to the curve-fit algorithm model. Excellent curve-fits were obtained for the initial data, as illustrated by the example in Figure C9 for the 500,000-gallon airfield elevated water storage tank. Table C1 provides a summary of the calculated polarization-decay projected values; again the coefficients of determination, or R^2 values, were very close to 1.0.

Figure C1. 500,000-gallon elevated water storage tank, Fort Leonard Wood, MO.

Figure C2. Test setup for polarization-decay measurements for tank shown in Figure C1.

Figure C3. Prototype data logger being used for polarization-decay measurements for tank shown in Figure C1.

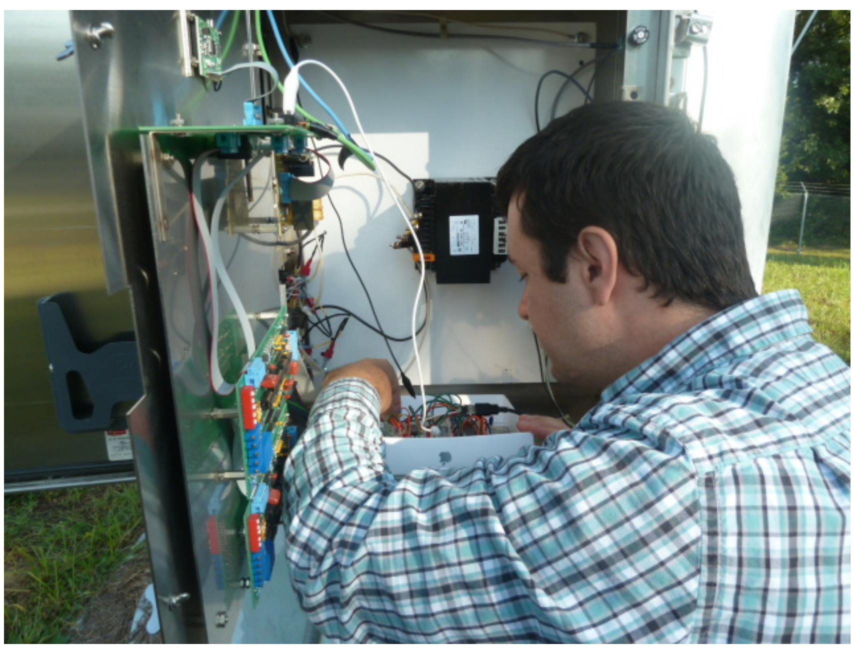


Figure C4. The 2.25-million gallon above-ground water storage tank at Fort Leonard Wood, MO.

Figure C5. Test setup for polarization-decay measurements for tank shown in Figure C4.

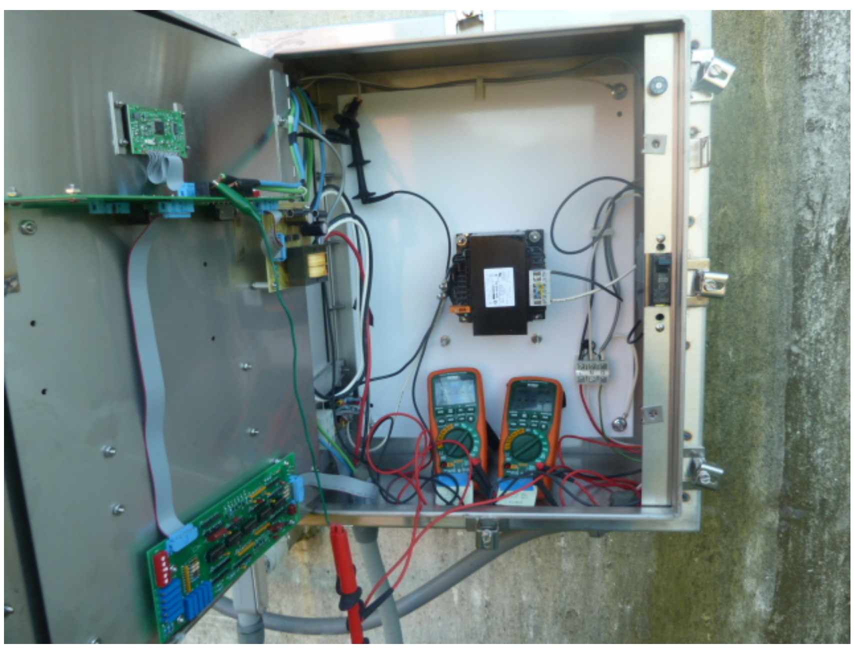


Figure C6. Prototype data logger being used for polarization-decay measurements for tank shown in Figure C4.

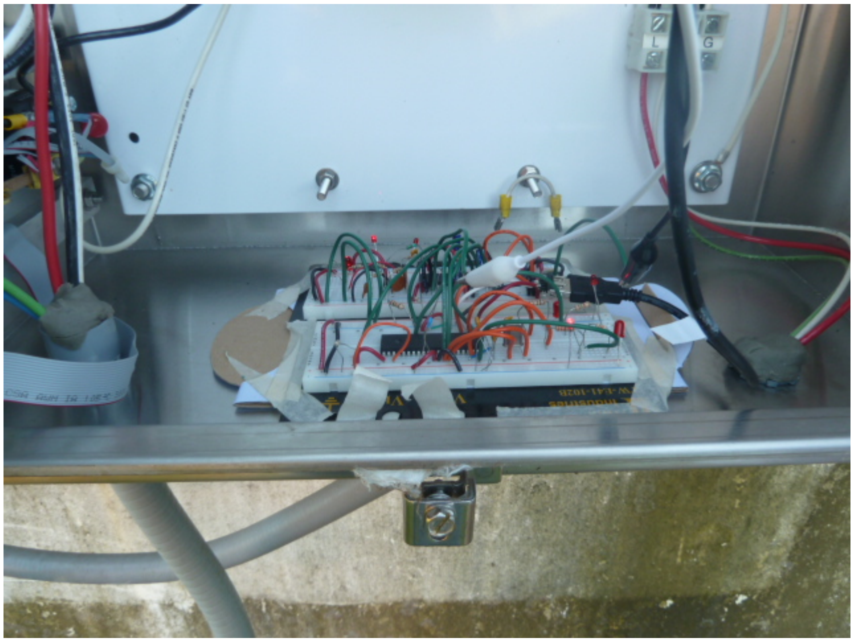


Figure C7. 500,000-gallon elevated water storage tank for airfield at Fort Leonard Wood, MO.

Figure C8. Test setup for polarization-decay measurements for tank shown in Figure C7.

Figure C9. Polarization-decay data and curve-fit trend lines for interior of 500,000-gallon elevated storage tank for airfield at Fort Leonard Wood, MO.

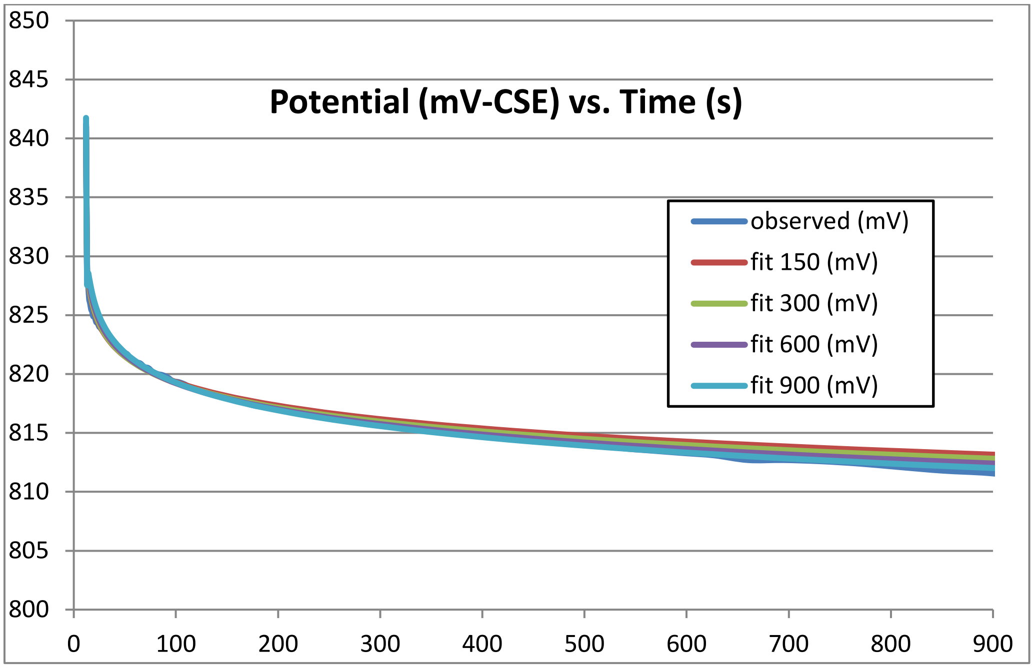


Table C1. Example of calculated polarization-decay values for 500M-gallon elevated airfield water storage tank at Fort Leonard Wood, MO, for extended time periods (up to 1 year) from initial data points (150 to 900) for the curves shown in Figure C9.

First measured value at 12 seconds	841.00 mV			
Final measured value at 50,000 seconds	724.80 mV			
Final **MEASURED** Polarization decay at 50000 seconds (Δ mV)	116.20			
	Fit 150	**Fit 300**	**Fit 600**	**Fit 900**
4-Hour Calculated Value (mV) (Polarization decay Δ mV)	805.66 (35.34)	804.99 (36.01)	804.07 (36.93)	803.13 (37.87)
12-Hour Calculated Value (mV) (Polarization decay Δ mV)	802.7 (38.3)	801.89 (39.11)	800.76 (40.24)	799.61 (41.39)
24-Hour Calculated Value (mV) (Polarization decay Δ mV)	800.82 (40.18)	799.94 (41.06)	798.68 (42.32)	797.39 (43.61)
48-Hour Calculated Value (mV) (Polarization decay Δ mV)	798.95 (42.05)	797.98 (43.02)	796.59 (44.41)	795.16 (45.84)
One-Year Calculated Value (mV) (Polarization decay Δ mV)	784.89 (56.11)	783.28 (57.72)	780.89 (60.11)	778.41 (62.59)
Coefficient of Determination, R^2 (fitted range)	0.99248	0.99526	0.99416	0.99051
Coefficient of Determination (150 points)	0.99248	0.99146	0.9875	0.97616
Coefficient of Determination (300 points)	0.99262	0.99526	0.99244	0.9838
Coefficient of Determination (600 points)	0.97207	0.98812	0.99416	0.98898
Coefficient of Determination (900 points)	0.92448	0.9591	0.98319	0.99051
Coefficient of Determination (full observed range)	-3.59393	-3.47854	-3.3206	-3.1628

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY)
September 2016

2. REPORT TYPE
Final

3. DATES COVERED (From - To)

4. TITLE AND SUBTITLE
Polarization Decay Fit for Assured Cathodic Protection of Steel Structures: Final Report on Project F12-AR03

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
Corrosion Prevention and Control

6. AUTHOR(S)
Thomas A. Carlson, Andrew P. Friedl, Charles P. Marsh, James P. Miller, James B. Bushman, Robert Bushman, and Bopinder S. Phull

5d. PROJECT NUMBER
F12-AR03

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Engineer Research and Development Center
Construction Engineering Research Laboratory
PO Box 9005
Champaign, IL 61826-9005

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC/CERL TR-16-20

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of the Secretary of Defense
3090 Defense Pentagon
Washington, DC 20301-3090

10. SPONSOR/MONITOR'S ACRONYM(S)
OUSD(AT&L)

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

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

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Corrosion is the number-one cause of damage to industrial waste lines, potable water distribution systems, heat distribution pipes, and underground storage tanks. Besides costing millions of dollars annually to repair, corrosion at military installations can adversely impact mission objectives through the catastrophic failure of mission-critical infrastructure. This project sought to develop a technology to quickly and more reliably predict the achievement of the NACE International 100 mV polarization shift cathodic protection criterion for large metallic structures. By basing the prediction on sufficient initial short-term data, any error associated with long-term environmental changes (e.g., moisture, temperature changes, and soil compaction) is avoided. Time savings for reduced measurement labor is a related benefit. Overall, the technology was validated at a proof-of-principle level. While not yet ready for immediate implementation, the technology merits further coordinated development. Wider testing and field demonstration, followed by a concerted and long-term criteria acceptance effort, are still required. Once fully implemented, the projected return on investment is projected to be 8.55.

15. SUBJECT TERMS
Metals--Corrosion fatigue, Corrosion and anti-corrosives, Cathodic protection, Structural health monitoring, Cooling towers, Underground storage tanks, Pipeline, Military bases, Rate of return

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (include area code)
Unclassified	Unclassified	Unclassified	UU	50	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18