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Advancement of Cathodic Protection Monitoring and Control for Water Storage Tanks

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6. AUTHOR(S) Chrissy Henderson, Ph.D., P.E., chenderson@usbr.gov Grace Weber, gweber@usbr.gov			5d. PROJECT NUMBER Final Report ST-2022-20023-01		
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14. ABSTRACT This research investigated use of ribbon anodes in a ring configuration as a method of cathodic protection (CP) for water tank interiors. Testing was performed using a laboratory model of a storage tank. The effectiveness of the CP system was determined by measuring polarized potentials and evaluating against NACE criteria for protection. This work also studied the performance of a polysiloxane coating system used in conjunction with the CP system. Findings showed polarized potentials around -1100 mV _{CSE} , which is the threshold for what Reclamation considers over-polarization from a CP system. Because of this, for field applications, designers should consider mitigation of over-polarization by using dielectric material on the anode or current/potential control techniques, such as auto-potential controllers. The visual coating inspection performed after 4.5 months in immersion found no signs of typical coating failure modes. Recommendations for future work include continued observation of the ribbon anode CP system and the polysiloxane system with further time in immersion, which will give insight to performance over the system lifetimes.					
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Advancement of Cathodic Protection Monitoring and Control for Water Storage Tanks

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prepared by

Technical Service Center

Chrissy Henderson, Ph.D., P.E., Materials Engineer

Grace Weber, Materials Engineer

Cover Photograph: Laboratory water storage tank filled with water and in-place at the Technical Service Center, Hydraulics Laboratory. (Reclamation/Grace Weber).

Peer Review

**Bureau of Reclamation
Research and Development Office
Science and Technology Program**

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Advancement of Cathodic Protection Monitoring and Control for Water Storage Tanks

**Prepared by: Chrissy Henderson, Ph.D., P.E.
Materials Engineer, Materials and Corrosion Laboratory, 86-68540**

**Checked by: Grace Weber
Materials Engineer, Materials and Corrosion Laboratory, 86-68540**

**Technical Approval by: Daryl Little, Ph.D.
Materials Engineer, Materials and Corrosion Laboratory, 86-68540**

**Peer Review by: Dave Tordonato, Ph.D., P.E.
Materials Engineer, Materials and Corrosion Laboratory, 86-68540**

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Acronyms and Abbreviations

AWG	American wire gauge
CP	cathodic protection
CSE	copper/copper sulfate reference electrode
FD	fast dry
GACP	galvanic anode cathodic protection
HMWPE	high molecular weight polyethylene
HSS	hydraulic steel structures or hydraulic steel infrastructure
Instant-OFF	polarized potential (also called IR free potential)
IR	Ohm's Law (current and resistance are multiplicative resulting in voltage)
Native	free corrosion potential of a structure in an electrolyte before any cathodic protection is applied
OFF	polarized potential (see instant-OFF)
ON	applied potential or ON potential
PVC	polyvinyl chloride
QA/QC	quality assurance and quality control
Reclamation	Bureau of Reclamation
TSC	Technical Service Center

Symbols and Measurements

d	anode diameter
ft	feet
ft ²	square feet
in	inch
l	anode length
lbs	pounds
mA	milliamps
mV	millivolts
mV _{CSE}	millivolts with respect to a copper/copper sulfate reference electrode
R	anode resistance
r_{tank}	radius of tank
V	volts
Ω	ohm
ρ	water resistivity
π	mathematical constant pi $\approx 3.14159...$
\pm	plus or minus
%	percent

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Executive Summary

The Bureau of Reclamation oversees more than a thousand water tanks on hundreds of projects in the Western United States. These include storage and regulating tanks, air chambers, and elevated tanks. Tank interiors can be expensive to reline, so for tanks with aging linings or for new facilities being designed, cathodic protection (CP) systems can be beneficial to extend the service life of the tank, as well as the protective coating by decreasing the frequency of the need for coating maintenance and replacement. Galvanic anode CP (GACP) systems in a circular hanging rod design are often specified for water storage tank CP; however, these can be cumbersome to install and can interfere with mixers or other equipment that may be present in the center of the tank.

This research sought to investigate different anode configurations for tank CP systems, namely by using surface-mounted magnesium ribbon anodes arranged in rings. These magnesium ribbon anodes were installed in the interior of a laboratory model of a water storage tank. While the anodes themselves are not novel, their use to protect tank interiors differs from Reclamation's traditional hanging rod GACP system design. The level of corrosion protection provided by the ribbon anodes was evaluated by measuring the native, ON, and instant-OFF (polarized) electric potentials with a reference electrode at various points along the tank wall and floor. Anode current output was also monitored to assess the system effectiveness. The polarized potential was compared to standard criteria set forth by NACE to establish if adequate corrosion protection was occurring. The study found that the system was meeting NACE corrosion protection criteria, but it was determined that a longer test period is required to better understand how the CP system would perform over the full lifetime.

This research also investigated some secondary items, including the use of coupons to measure instant-OFF and the performance of a polysiloxane coating system in immersion service. Coupons can be useful to obtain instant-OFF measurements on direct-connect anodes that can't be "turned off." The study found that coupons can be used for these kinds of field measurements; however, care must be taken to correctly interpret the results, as there can be differences between coupon readings and actual measurement value based on age of coating and the number of defects present. The polysiloxane coating system was used on the tank and coupons, and as part of the research study, it was evaluated for performance in immersion with CP applied. The first inspection at 4.5 months of immersion revealed that the coating remained in good quality. A longer test duration is needed to gain a better picture of coating performance over the lifetime, especially in the highly polarized regions near the anodes.

1. Introduction

As part of its water infrastructure inventory, the Bureau of Reclamation oversees more than a thousand water tanks on hundreds of projects in the Western United States. These include storage and regulating tanks, air chambers, and elevated tanks. The tank interiors are filled with water to varying levels based on system needs, making them prone to corrosion. Tank interiors can be expensive to reline, so for tanks with linings approaching the end of their service life or for new facilities being designed, cathodic protection (CP) systems can be beneficial to extend the service life of the tank, as well as the protective coating by decreasing the frequency of the need for coating maintenance and replacement.

It is typical at Reclamation to install galvanic anode CP (GACP) systems on water storage tanks. These systems use the principle of the galvanic series where a more active metal, such as magnesium, is electrically connected to the more noble structure metal, typically mild steel. The active metal will then become the anode in the corrosion cell and will sacrificially be consumed in the oxidation reaction to protect the metallic structure (cathode). These systems are commonly designed for a 20-year service life and require little maintenance. However, the vertically hanging galvanic rod anode designs currently used can be cumbersome to install and can interfere with mixers or other objects that may be present in the center of the tank.

This research sought to examine a CP system design for tank interiors using surface mounted magnesium ribbon anodes arranged in rings. While the anodes themselves are not new, their use to protect tank interiors differs from Reclamation's traditional hanging rod GACP system design. The objective of the work was to determine the feasibility of implementing a ribbon anode CP system, which would be easier to monitor, replace, and install than the traditional hanging rod anode system typically used by Reclamation in tanks. The ribbon anode system also has potentially broader application than the traditional system due to internal features in some of Reclamation's tanks, for example mixers, which may prevent the use of hanging rod anodes.

The level of corrosion protection provided to a structure by CP can be evaluated by measuring the structure's polarized potential with a reference electrode. The polarized potential is compared to standard criteria set forth by NACE to establish if adequate corrosion protection is occurring. The polarized potential is measured at various locations on a tank to gauge the health of the whole interior surface; this is important because CP protection can vary across the structure depending on geometry and other factors. So the use of reference electrodes in a grid-like pattern allows for local differences in polarized potential to be captured [1].

As another part of capturing polarized potential measurements, coupons are often used as a tool to help assess the level of polarization of a structure [2]. Coupons can be used to obtain approximate instant-OFF (also referenced as OFF) measurements of structures when an anode system cannot be disconnected, and a polarized (IR free) potential can't be determined. This research utilized coupons mounted inside of the tank to determine the reliability of the coupon method and give a comparison to tank measurements.

2. Laboratory Testing Set-up

The steps for set-up of laboratory testing include: model tank construction, CP system design, and CP system installation. Each step will be discussed in the sections below.

2.1 Model Tank Construction

To prepare for laboratory testing, researchers first designed and constructed a model steel water storage tank. The model tank had a diameter of 12 feet (ft) and a height of 8 ft, with a maximum water storage capacity of 7.5 ft. These dimensions were chosen as the maximum size allowed in the given space on the laboratory floor and based on the size of the bay doors entering the building.

Tank construction was done in-house using mild steel panels. All construction steps, including assembly, surface preparation, and coating application, were done with the tank in two halves so that it would fit through the laboratory bay doors for installation in the Technical Service Center (TSC) Hydraulics Laboratory. The construction steps are listed below, with pictures shown in Figure 1–Figure 4. After construction was completed, the tank was water tested for leaks.

1. The tank bottom and wall panels were welded together for each tank half.
2. A temporary confinement structure was erected around the tank halves for surface preparation (abrasive blasting) and protective coating application of the tank interior
3. The tank halves were abrasive blasted with steel grit to near-white metal following SSPC-SP10/NACE No. 2 [3], to remove visible contaminants and provide a clean surface for coating application.
 - a. Spot measurements of surface profile were made for quality assurance and quality control (QA/QC). This data is included in Appendix A.
4. Portions of the tank surface within 6 inches (in) of future welds were masked with plastic liners and tape.
5. Three coats of polysiloxane protective coating system (Sherloxane 800 Fast Dry (FD)) were applied at 4–6 mils thick per coat using conventional spray equipment following manufacturer recommendations.
 - a. Environmental measurements were collected prior to each spray application as part of QA/QC. This data is included in Appendix A.
 - b. Spot dry film thickness measurements were made for QA/QC. This data is included in Appendix A.
 - c. Holiday (defects in the coating) testing was performed using NACE SP0188 [4].
 - d. Holidays were repaired by hand sanding and applying 3 coats of Sherloxane 800 FD.
6. The tank halves were brought into the Hydraulics Laboratory and welded together.
7. The remaining bare areas around the weld zones were cleaned with grinders to remove visible surface contaminants and prepare for coating application.
8. The same coating system was roller applied within the system's re-coat window to the bare areas and overlapped on the surrounding areas of the tank interior following manufacturer recommendations and with appropriate QA/QC.



Figure 1.—Temporary confinement structure around tank halves for abrasive blasting and coating application (left) and a close-up of one tank half prior to abrasive blasting (right).



Figure 2.—Abrasive blasting of a tank half (left) and subsequent masking of 6-in margins for future tank support ring and tank half edge welding zones with plastic liners and tape (right).

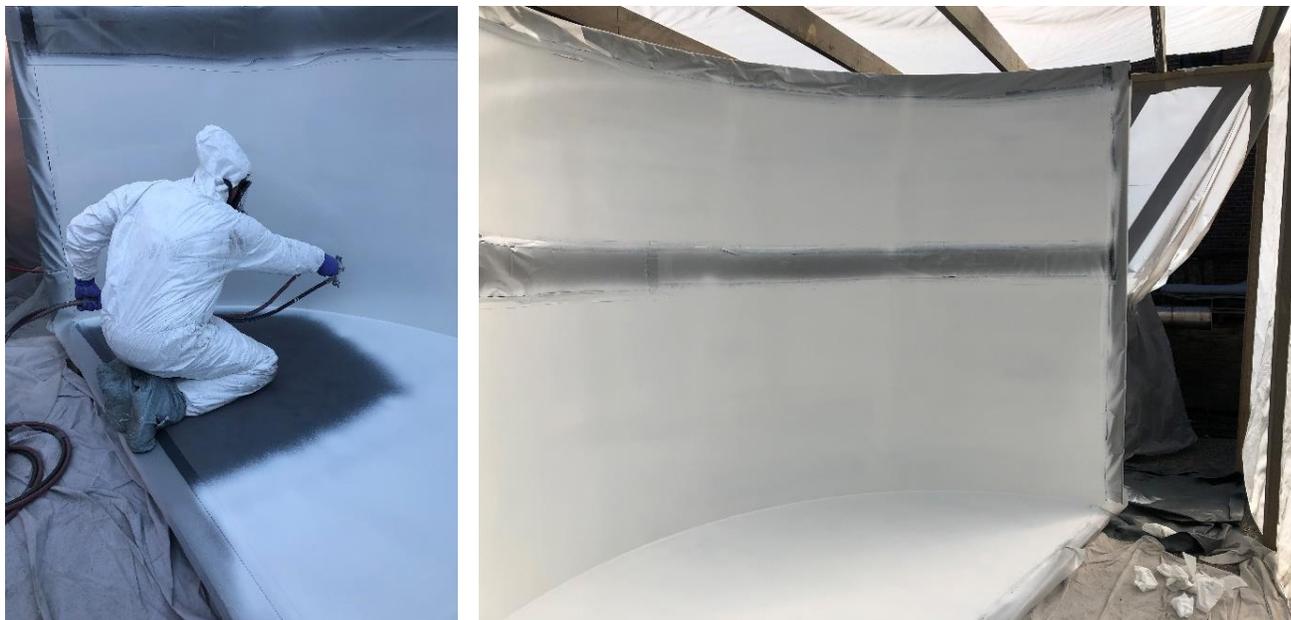


Figure 3.—Spray application of protective coating system (left) and close-up of one tank half after completion of the protective coating application (right).



Figure 4.—Grinding of bare steel areas after completion of welding (left) and roller application of protective coating system to the bare areas (right).

2.2 Cathodic Protection System Design

While the model tank construction was occurring, researchers simultaneously worked on a cathodic protection design for the CP system. The CP system design was a GACP system, which utilized the following assumptions:

- Water resistivity was calculated as the inverse of water conductivity, which was measured to be 2,740 Ω -cm using a benchtop conductivity probe.
- The design life was set to 20 years, as is common for CP system design work. The system is sized to provide protection based on the assumed structure condition at the 20-year mark.
- The submerged structural surface area was calculated to be 395.70 square feet (ft^2) based on a 12 ft diameter and 7.5 ft water elevation.
- Assumed bare surface area at the 20-year mark was chosen as 2%.
- A current density of 0.05 milliamps/square foot (mA/ft^2) was assumed by using tables of approximate current densities for CP of steel in various flow rates and conditions [5], along with experienced judgment. The tank contains stationary neutral potable water, as opposed to high flowing or salty water.
- Protection of the tank is established via CP design driving voltage, following the NACE SP0169 [6] criterion that a polarized potential must be no less negative than -850 mV with respect to a copper/copper sulfate reference electrode (CSE).
- Circuit resistances consider the resistance of the tank, the #12 American Wire Gauge (AWG) cables, and the anodes.
- Ribbon anodes do not fit the traditional anodes found in the CP system design resistance tables, which consider the anode geometry, position related to the surface, and orientation [1]. Therefore, two methods were used for determining anode resistance to remote earth¹, and an average was used for the CP design:
 - Method A: Anode assumed to be a long, slender, surface-mounted rod in a horizontal orientation from the tank wall surface, using the following equation [1]:

$$R = \frac{\rho}{\pi l} \ln\left(\frac{2l}{d}\right)$$

- Method B: Anode assumed to be a ring-shaped ground band, typically seen in CP systems installed underneath tank bottoms, of a band radius equal to the tank radius, using the following equation [1]:

$$R = \frac{\rho}{2\pi^2 r_{\text{tank}}} \ln\left(\frac{16r_{\text{tank}}}{d}\right)$$

- For both Method A and B, the anode gradients were assumed to move in a radial direction away from the wall towards the center of the tank. Note that in the equations above, R =anode resistance, ρ =water resistivity, π =mathematical constant, π ($\approx 3.14159\dots$), l =anode length, d =anode diameter, and r_{tank} =tank radius.

¹ Remote earth is defined as a point, mathematically, that is far enough from the anode that the potential gradients with respect to the structure (i.e., tank) do not change.

2.3 Cathodic Protection System Installation

With the model tank constructed and the CP system designed, the next step was for researchers to install the CP system, including the anodes, test coupons, reference electrodes, and junction boxes and associated electrical components.

2.3.1 Anodes

The ribbon anode GACP system consisted of four 37.3-ft-long, high-potential magnesium ribbon anodes with a 3/4-in by 3/8-in cross section. Each anode weighed approximately 9 pounds (lbs). The anodes were shipped in tightly rolled bundles, so researchers had to re-form each bundle to create a ring of the proper diameter to sit along the inside walls of the tank. Each anode came equipped with a short, factory-installed wire rod at one end.

Each ribbon anode was suspended by four evenly spaced ropes, as shown in Figure 5, which allowed for changes in anode position during testing. The sets of ropes were labeled 1–4 to differentiate the four anodes. To prevent damage to the tank's coating, the ends of each anode were taped with electrical tape and rubber spacers (Figure 6) were attached at several points along the outside of each anode ribbon, keeping them off the tank wall.



Figure 5.—Ribbon anodes suspended at precise elevations by ropes (left) and anchoring of the ropes on the exterior of the tank (right).



Figure 6.—Heat shrink tubing being applied over the splice between the anode lead and the ribbon anode factory-installed wire.

For the anode lead, a cable rated for water immersion service (#12 AWG, stranded copper, with high molecular weight polyethylene (HMWPE) insulation) was spliced to each of the factory-installed wires on one end of the ribbon anodes. The splice was crimped and potted in epoxy using a pump wire splice kit, and then covered with heat shrink tubing, which provided secondary protection from water exposure, as shown in Figure 6. The four anode leads were run over the top of the tank and down the exterior to Junction Box 2.

2.3.2 Test Coupons

Researchers prepared six mild steel coupons (3-in by 5-in by 1/8-in) by degreasing and abrasive blasting to near-white metal, and then applying the same protective coating system as was used on the tank. A portion of coating was ground off of one face of each coupon with a rotary tool, as shown in Figure 7, to provide a bare metal area for exothermic welding of a #12 AWG cable.



Figure 7.—Test coupons with bare metal area for exothermic welding of #12 AWG cable.

After exothermically welding a lead onto each coupon, bitumastic was used to repair the coating and cover all bare metal except for a circle (1/2-in diameter) to act as a holiday of known surface area

(Figure 8). Finally, a permanent CSE rated for immersion was strapped to each coupon with self-adhering tape. The tip of each reference electrode was positioned to be near to the coupon holiday (Figure 8).

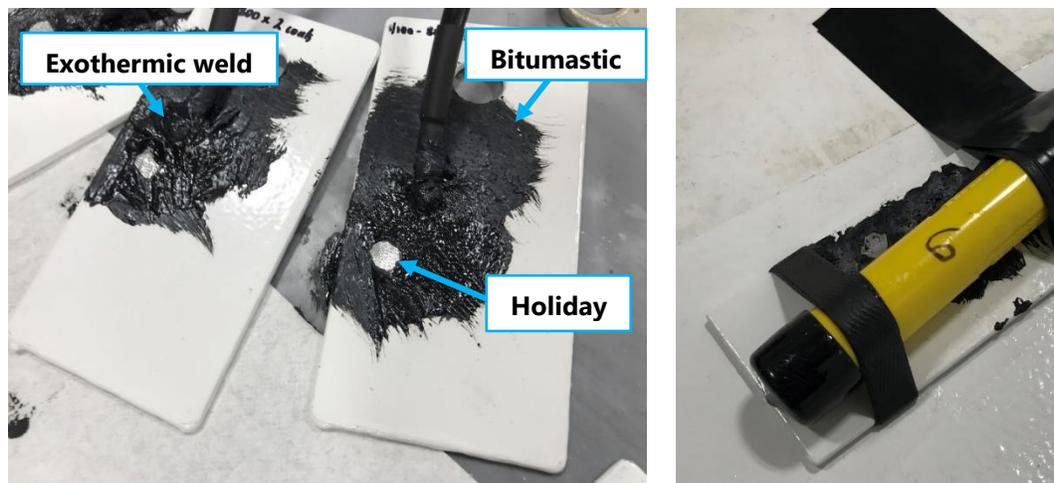


Figure 8.—Two test coupons with bitumastic coating repair over the exothermic weld, leaving a bare steel holiday of known size (left). A reference electrode strapped to a test coupon (right).

Each of the six-test coupon/reference electrode bundles were secured to the tank interior with silicone adhesive. Electrical tape held each bundle in place while the silicone cured. The position of the six test coupon bundles is shown in Figure 9, below, with four positioned on the tank wall and two positioned on the tank floor.



Figure 9.—Reference electrodes on the tank interior wall (left) and the center of the tank floor (right).

2.3.4 Junction Boxes

Two junction boxes housed the shunts, coupon connections, reference electrode connections, and anode cable connections, which were used for taking measurements to verify system performance. The junction boxes were set up on the exterior of the tank, as shown in Figure 10.

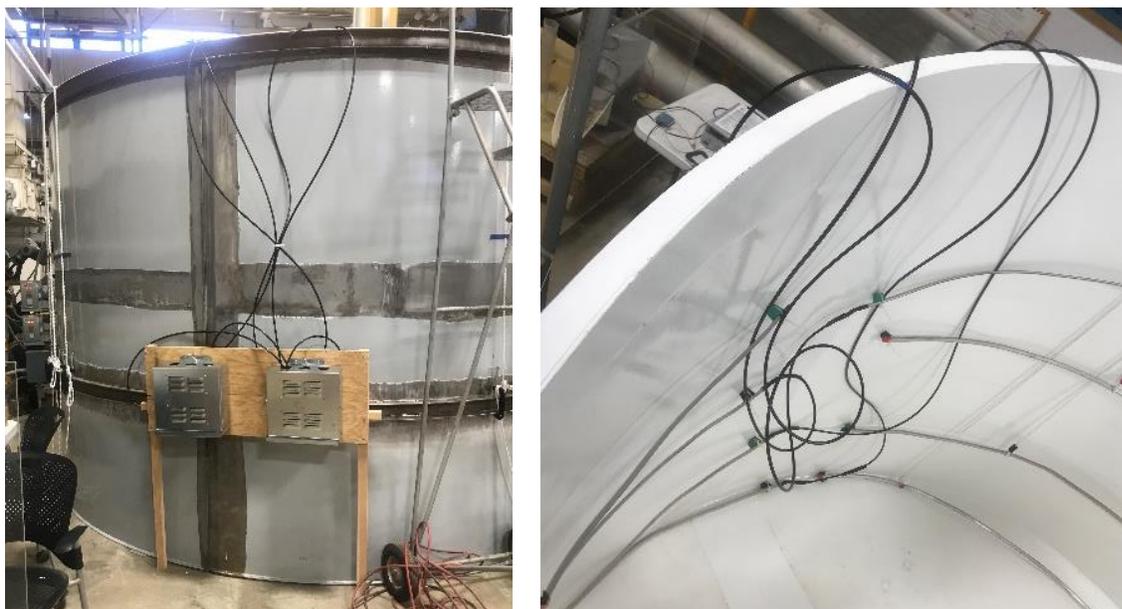


Figure 10.—Exterior junction box placement (left) and anode cable connections (right).

The left junction box, labeled Junction Box 1, housed the coupon and reference electrode connections, labeled C1-6 and R1-6 respectively (Figure 11).

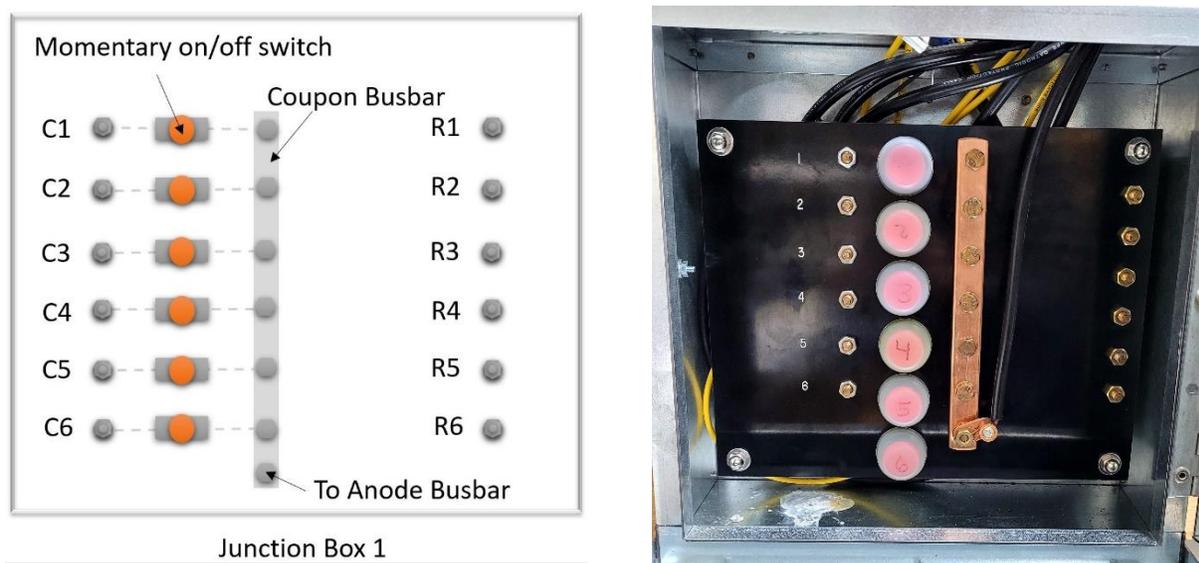


Figure 11.—Schematic of Junction Box 1 layout (left) and photograph of Junction Box 1 (right).

The right junction box, labeled Junction Box 2 (Figure 12), housed the anode connections, labeled A1-4, and used 0.1 Ω shunts that provided measurement options for determining the anode output in mV.

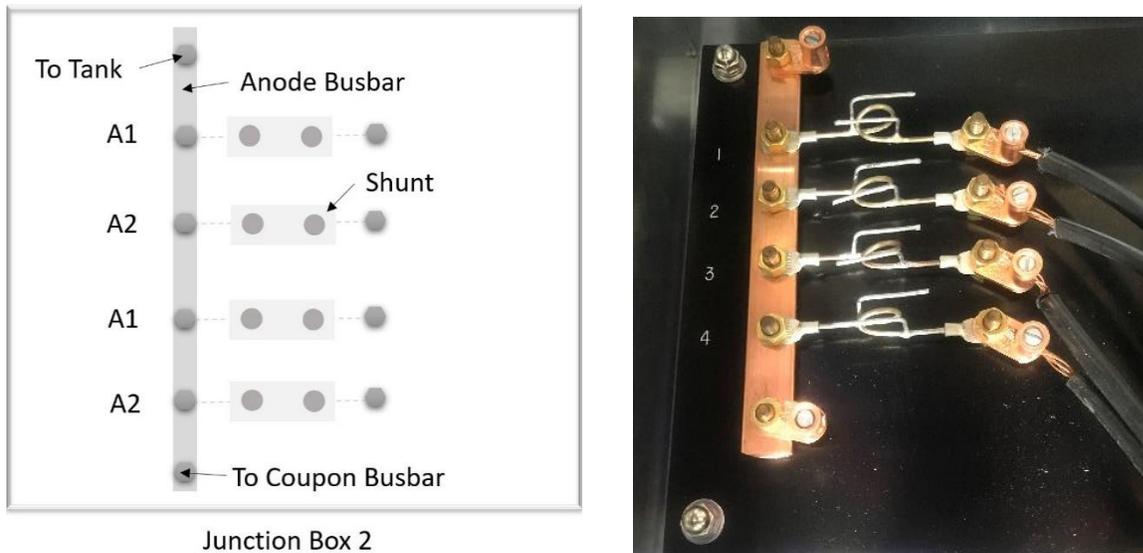


Figure 12.—Schematic of Junction Box 2 layout (left) and photograph of Junction Box 2 (right).

3. Laboratory Testing Methodology

The purpose of laboratory testing was to determine the performance of the ribbon anode system and its ability to provide corrosion protection to the tank model. To make this determination, the following measurements and inspections were performed:

- Tank-to-electrolyte potential measurement
- Coupon potential measurement
- Anode output measurement
- Protective coating inspection

Prior to making any measurements, the tank was filled to 7.5 ft water elevation, and the water level was maintained between 7.25–7.75 ft for the duration of these tests. Markings on the tank exterior were used to indicate the heights of the anodes to ensure that they did not shift over time.

Prior to the protective coating inspection, the tank was fully drained, allowing for a close inspection of the coating condition within the tank interior.

3.1 IR Drop

IR drop is defined as “the voltage across a resistance when current is applied in accordance with Ohm’s law” [7]. CP current flows towards the structure through all available paths, making the measured potential on the structure appear more negative while current is flowing. The effect is that, while CP current is being applied, a structure appears better protected from corrosion than the true protection level. Structures with newly applied coatings tend to create a greater IR drop because fewer defects are present. IR drop is removed from electric potential measurements by taking instant-OFF measurements. If the only current producing the IR drop is the CP current, as is the case with our experimental set-up, this current can be interrupted, and an instant-OFF measurement collected to provide the polarized potential of the protected structure [8].

3.2 Tank-to-electrolyte and Coupon Potential Measurements

To evaluate the corrosion protection provided by the CP system, researchers measured the tank’s polarized potential with a CSE. Prior to connecting the CP system, native potentials were measured for the tank and each coupon. ON and instant-OFF potentials were taken at regular intervals for both the coupons and the tank at each reference location (Figure 13).

The figure shows the four anodes placed at different elevations on the tank interior, A1-A4. The reference electrode placement followed a grid pattern down the wall and along the tank bottom, indicated by R1-R6 for the tank measurements and C1-C6 for the coupon measurements. The effects of voltage drop through the electrolyte and coating were discerned by measuring ON and instant-OFF at the reference electrode positions for the tank and coupon potential measurements.

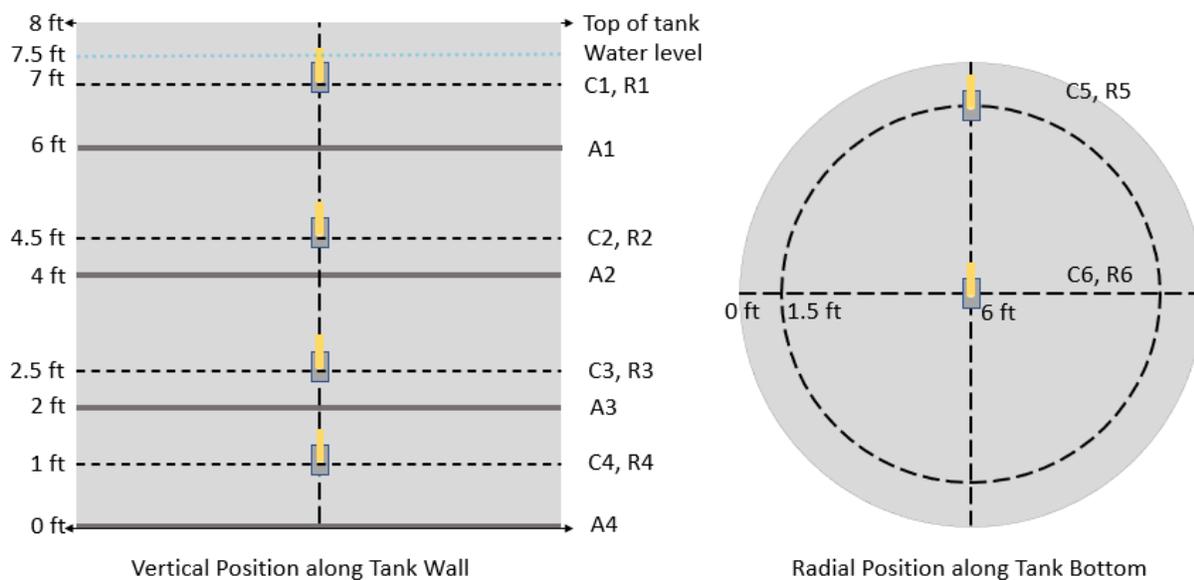


Figure 13.—Schematic of anodes (A), coupons (C), and reference positions (R) with respect to the 8-ft-tall, 12-ft-diameter model test tank.

Coupons are used to determine the level of corrosion protection from a CP system that a structure is experiencing when the structure can't have the CP current interrupted for an instant-OFF measurement. Coupons have been shown to be an effective tool in the corrosion industry since the 1930's [2]. The coupons in this test were mild steel, like the tank, and coated with the same coating system as the tank. A known defect was added, and the coupon was connected to the tank and to the tank CP system to allow for measurement of the ON and instant-OFF of the coupon. The goal for this portion of the research was to determine how reliable the coupon method would be for determining the tank instant-OFF measurement. This is relevant for CP systems with direct-connect anodes that cannot be interrupted, as is common in some CP installations.

Originally, permanent reference electrodes made for water immersion were placed at all the reference positions in the tank (Figure 9). After two weeks of testing, the potential difference between several of the permanent reference electrodes and a laboratory reference electrode was greater than plus or minus (\pm)5 mV, indicating loss of functionality. The electrodes were demonstrating a lack of stability and were leaking copper sulfate solution, as demonstrated by the blue coloring surrounding the reference electrode (Figure 14). To prevent further problems with the reference electrodes, researchers de-watered the tank and removed the permanent reference electrodes. This occurred after 135 days of testing.

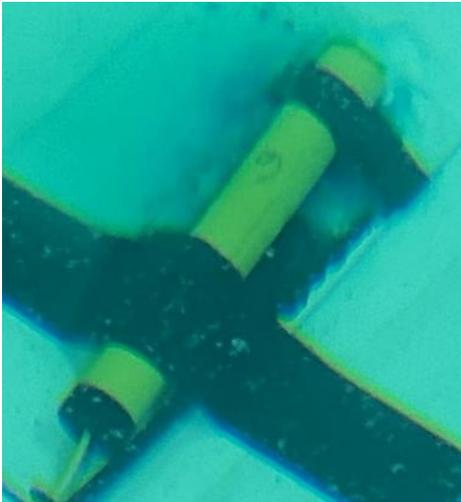


Figure 14.—Leaking reference electrodes as evidenced by blue copper sulfate crystals surrounding electrode.

In lieu of the permanent reference electrodes, a portable reference electrode was mounted on the end of a 12-ft long polyvinyl chloride (PVC) pole, which researchers could extend down into the tank to reach each measurement location.

The experimental testing periods when the CP system was connected are described in Table 1.

Table 1.—Tank CP Testing Periods

Test	Period	Comments
Test 1	Days 1–111	All four anodes connected for 111 days.
Test 2	Days 111–135	Only Anode 1 connected for 24 days.
---	Day 135	Tank dewatered to remove the permanent reference electrodes, and then refilled.
Test 3	Days 135–183	All four anodes connected for 48 days.
Test 4	Days 183–238	Only Anode 4 connected for 55 days.

Due to initial issues with completely interrupting the CP system, instant-OFF measurements did not start until day 67.

3.2 Anode Output

Anode current outputs were determined using a shunt in line with each anode connection in the junction box (Figure 12), using a voltmeter and conversion calculation. These measurements did not start until day 67 of testing, when the original shunts were resized and replaced so that the voltage drop measurement was detectable with the portable voltmeter.

3.3 Coating Inspection

The inspection of the polysiloxane system looked for typical coating failure modalities by visual inspection, following certain ASTM standards, listed below:

- ASTM D1654- “Standard Test Method for Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments” [9]
- ASTM D610- “Standard Practice for Evaluating Degree of Rusting on Painted Steel Surfaces” [10]
- ASTM D661- “Standard Test Method for Evaluating Degree of Cracking of Exterior Paints” [11]
- ASTM D660- “Standard Test Method for Evaluating Degree of Checking of Exterior Paints” [12]
- ASTM G8- “Cathodic Disbonding of Pipeline Coatings” (visual assessment only) [13]
- ASTM D714- “Standard Test Method for Evaluating Degree of Blistering of Paints” [14]

This inspection was performed during the tank de-watering cycle that occurred on day 135. During the de-watering, a defect was added by a razor blade on the tank wall next to Anode 4 that measured 6-inches long. In future work, the added defect would allow for determination of the resiliency of the polysiloxane coating to cathodic disbondment.

4. Results and Discussion

To verify that a CP system is properly and effectively providing corrosion protection, at least one of several NACE criteria must be met. These criteria are described in NACE SP0169 [6] and NACE SP0196 [15]:

- -850 mV criteria—tank-to-electrolyte polarized potential (instant-OFF) of -850 mV or more negative as measured with respect to a CSE.
- 100-mV shift criteria—a minimum of 100 mV of polarization, between the native and the instant-OFF potential.

Reclamation, in general, requires that the -850 mV criteria is met, but the 100 mV shift criteria is an alternative that is used depending on the situation (i.e., galvanic systems in high resistivity electrolytes, high velocity flows, or poor coating quality).

In addition to these criteria, Reclamation defines over-protection (also called over-polarization) as occurring with polarized potentials more negative than -1100 mV with respect to a CSE. Field and laboratory observation have shown that damage can occur on certain coatings with over-protection.

4.1 Tank-to-Electrolyte and Coupon Potential

The measured tank-to-electrolyte potentials are displayed in Figure 15, and the full data set is located in Appendix B. The IR drop can be determined by subtracting the ON potential from the instant-off potential and was shown to have an average value of 367.6 ± 5.7 mV. This IR drop is expected to decrease as the coating develops more defects over time.

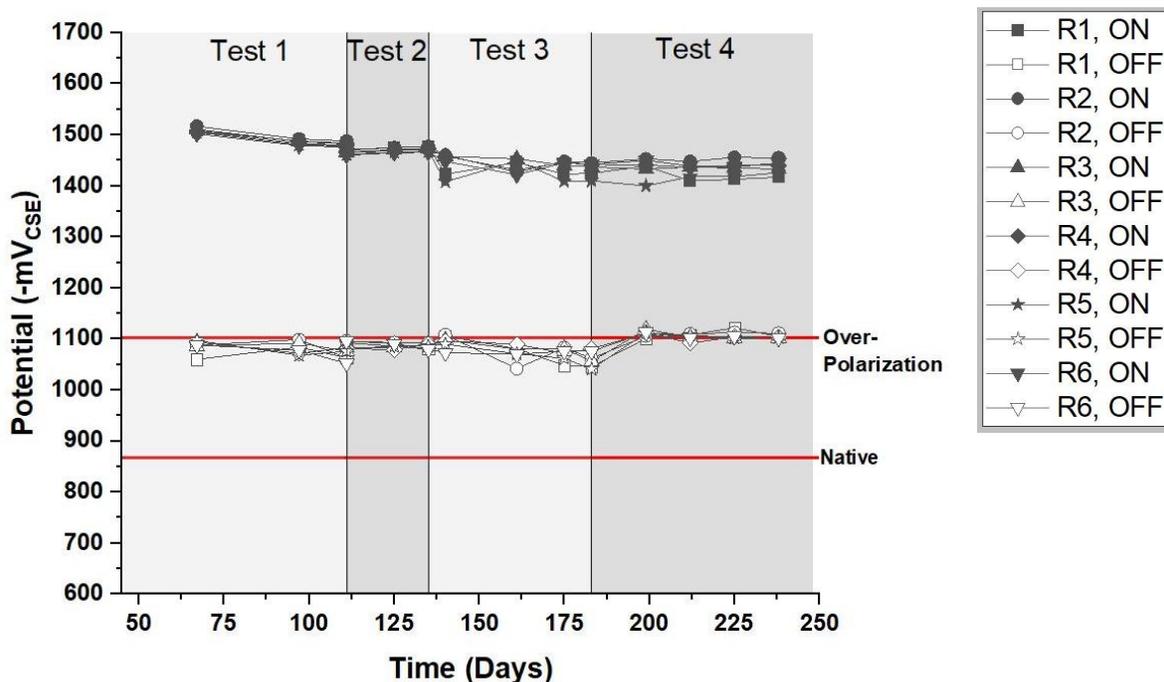


Figure 15.—Tank ON, instant-OFF, and native potentials for the four testing periods.

The potential measurements in Figure 15 show that both the NACE -850 mV and 100 mV shift criteria have been met (i.e., all instant OFF potentials were more negative than -850 mV with respect to a CSE, and the difference between the instant-OFF measurements against the native potentials is greater than 100 mV). The native potentials are shown by the horizontal “native” lines in Figure 15 and Figure 16.

For Test 2 (days 111–135) and Test 4 (days 183–238), only one anode was in use as part of the CP system. It is notable that over-polarization occurred in all tests, regardless of whether one anode or all four anodes were in use. It is hypothesized that this could occur during the beginning of a coated tanks life for a well applied coating system with minimal defects. Because the cathodic protection system is built to last 20 years, this tends to result in less need for the supplied voltage from the anodes, but at the end of its service life more current output from the anodes is necessary. At this point in the tanks life, the CP system is overdesigned for the needs of the tank.

Over-polarization could have been mitigated through the use of dielectric material (e.g. bitumastic, plastisol, or electrical tape) to reduce the exposed anode surface area, as is commonly seen in the field. For the purposes of the research, because no dielectric material was included, researchers were able to observe how the polysiloxane reacted to over-polarization. Other ways to mitigate over-polarization would be use of variable resistors or an auto-potential controlling device. Ribbon anodes only come in high potential options for purchase (-1700 mV) as opposed to a standard potential option (-1500 mV), so an auto-potential controller could reduce the anode output to an appropriate level to provide protection. Auto-potential controllers maintain a specified voltage between a reference electrode and the tank and will automatically adjust the anode current output as the needs of the CP system change.

Coupon potentials were measured and are shown in Figure 16, and the data set is located in Appendix B. The ON and instant-OFF potentials measured from the coupons showed an average IR drop of 350 ± 18 mV, which is lower than the value obtained with the tank-to-electrolyte measurements. This is consistent with the presence of defects; the coupon has a defined defect that was intentionally introduced, whereas the tank coating is new and relatively defect-free.

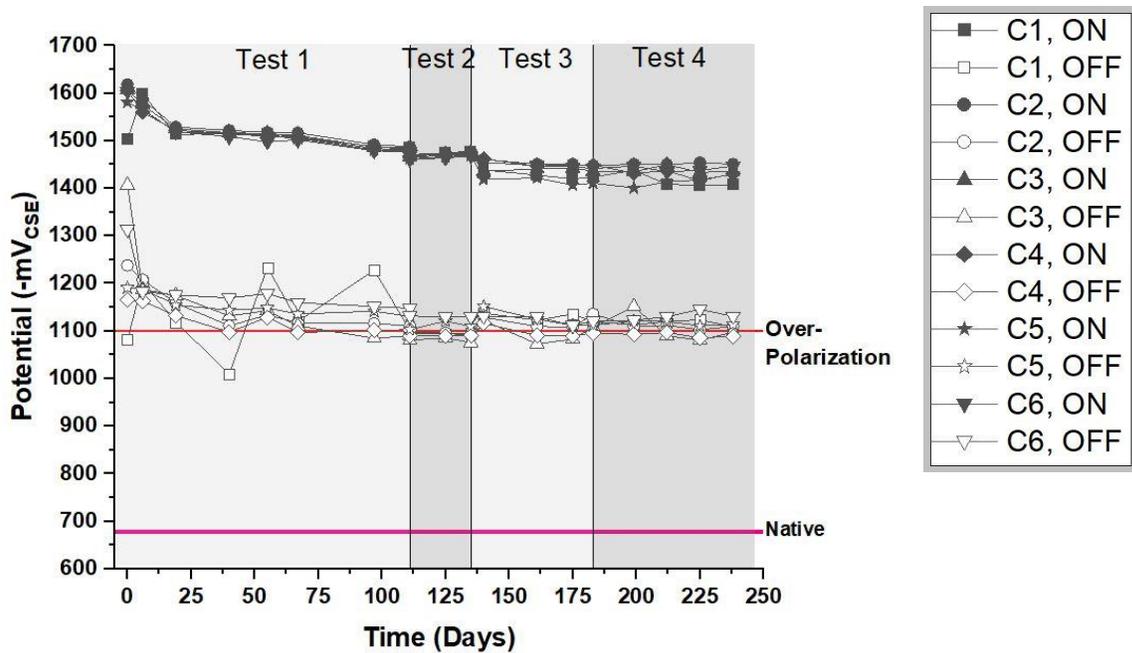


Figure 16.—Coupon ON, instant-OFF, and Native Potentials for test coupons.

As shown in the figure, the coupon measurements agree with the tank-to-electrolyte measurements that both the NACE -850 mV and 100 mV shift criteria have been met. It should be noted that the native potentials for the coupons were less electronegative, at -676.8 ± 4.4 mV, compared with roughly -867.3 ± 3.7 mV for the tank. The ON and instant-OFF coupon measurements showed fluctuations at the beginning of testing but stabilized as the polarization of the coupons progressed. This instability was not seen in the tank-to-electrolyte potentials (Figure 15) because these measurements were not collected until day 67, giving the tank time to stabilize. This initial fluctuation and subsequent stabilization of electric potential mirrors what is typically seen when CP systems are initialized in the field.

The coupons experienced greater over-polarization than the tank, which may be due to each coupon's intentional defect that made up approximately 0.6 % of the total coupon surface area. The tank had no intentional defects added, until day 135, when a 6-in scratch was introduced on the wall next to Anode 4. The exposed surface area from the scratch was less than 0.01% of the tank's immersed surface area.

Comparison of the instant-OFF potential between the coupons and the tank show that the values for the coupons are more negative by an average of 41 ± 15.5 mV. This demonstrates how use of coupons to obtain instant-OFF potentials can over-estimate protective potentials and could cause CP engineers to assume the tank is more protected than it is. In the case of this experiment, tank-to-electrolyte potentials were measured in addition to the coupon values, and these measurements confirm that polarized potential values are well above protection criteria. However, in a situation where only coupon potentials are being measured, and the values are not much more negative than the -850-mV potential, there could be a scenario where criteria appear to have been met when it really has not been met.

This discrepancy in instant-OFF values could be due to the test coupons having relatively larger sized defects as compared with the tank. In future work, a longer duration of testing with the addition of more purposeful defects on the tank would help further evaluate the reliability of using coupons to evaluate protection of field structure in a direct-connect system scenario.

The use of coupons is still a favorable general practice, but it is important for engineers that are interpreting the potentials to understand that there may be some discrepancy between a structure and the coupon.

4.2 Anode Output

Anode output allows for determination of how the CP system is drawing from each anode. Table 1 includes selected current output data for each anode during all four tests, including high and low current output values, average current output, and operating average anode current density. A table with the full anode output data as measured is in Appendix B. During Test 1 and Test 3 (when all anodes were in use), it became apparent that one anode was the primary anode for the system, providing most of the CP current to the structure. Anode use in a CP system is controlled by circuit resistance and proximity to sources of current draw (i.e., defects). Anodes with lower circuit resistance will be used preferentially over anodes with greater circuit resistance, and anodes next to a defect will dominate over anodes not nearby defects.

Table 2.—Summarized Anode Current Outputs

Test/Anode	High Current Output (mA)	Low Current Output (mA)	Average Current Output (mA)	Operating Average Anode Current Density (mA/ft ²)
Test 1:				
Anode 1	0.3	0.2	0.27	0.15
Anode 2	1.2	0.2	0.82	0.47
Anode 3	0.1	0.0	0.03	0.02
Anode 4	0.3	0.2	0.27	0.15
Test 2:				
Anode 1	1.3	1.0	1.17	0.67
Test 3:				
Anode 1	0.7	0.3	0.50	0.29
Anode 2	0.4	0.2	0.25	0.14
Anode 3	0.4	0.0	0.12	0.07
Anode 4	1.8	1.0	1.42	0.81
Test 4:				
Anode 4	1.5	--	1.50	0.86

As seen in Table 2, the low outputs for Anode 3 show that this anode got very little use during Tests 1 and 3. It is hypothesized that the circuit resistance is higher for that anode, which could be due to the splice or the wire connection to the junction box having greater resistance than for the other anodes. In Test 3, after the tank de-watering when a defect was purposefully added near Anode 4, you can see the primary anode shift from Anode 2 to Anode 4. In this case, the added defect was a

source of current draw, which increased the need for Anode 4 to put out more current. Anode current outputs for each test are shown in Figure 17.

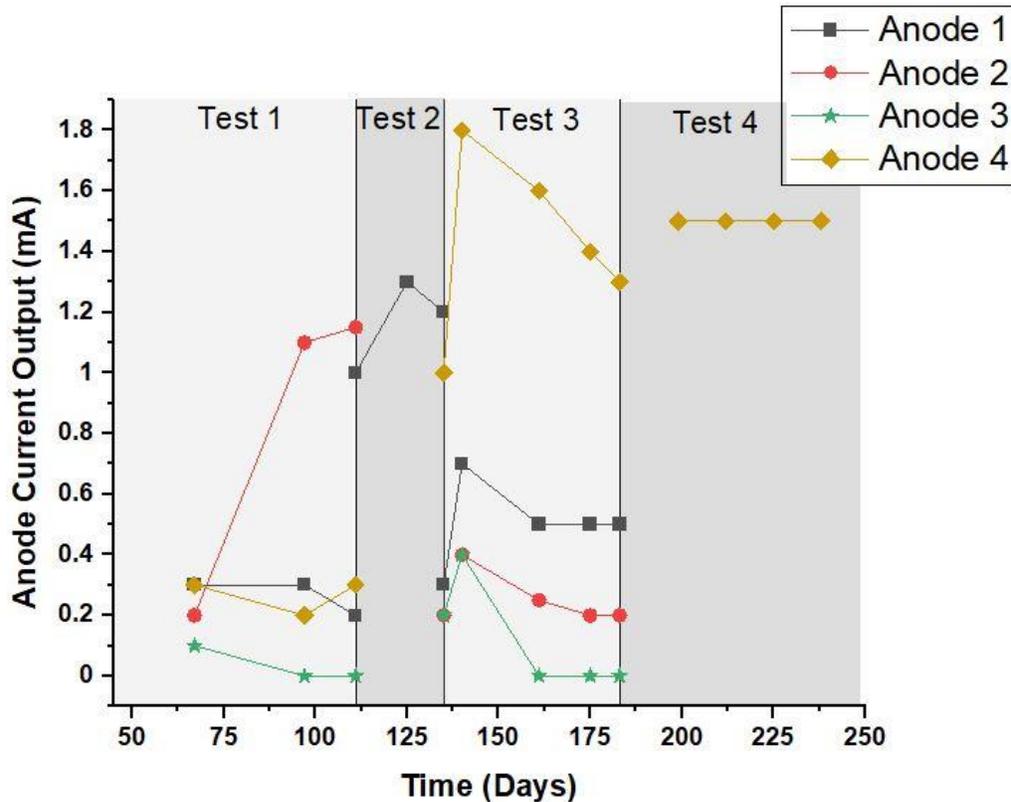


Figure 17.—Anode current outputs for each test.

According to Gummow, anode current density directly affects its electrochemical capacity and efficiency. As the anode current density approaches zero, the capacity, and thus efficiency, falls off dramatically. At current densities below 15 mA/ft², anode self-corrosion becomes the predominant mechanism of anode consumption [16]. For the best efficiency of ribbon anodes, an operating current density should be at least 20 mA/ft², which is not being reached by the anodes in this research. This is because for coated structures, at the beginning of the coating life, there are minimal defects, and therefore a higher system resistance and less anode output required to protect the system. However, as a coating deteriorates, the anodes shift primarily from self-corroding to more active sacrificial corrosion to protect the tank. Over time, the anode current density should increase, and thus efficiency as well.

More long-term testing is needed to see how quickly the anodes are consumed, and at the end of the long-term testing, the anodes should be weighed and compared to their original weights. Then an actual, rather than theoretical, consumption rate can be determined and compared to design assumptions.

4.3 Coating Inspection

After 135 days (4.5 months) of immersion, a visual coatings inspection was performed while the tank was de-watered. The coating inspection found no signs of any typical coating failure modes. To truly ascertain long-term performance of the polysiloxane coating system, it is recommended to continue to monitor the coating condition in immersion with CP applied for a longer evaluation period to assess true coating performance.

The anodes were over-polarizing the tank for parts of the testing period in this research, which can correlate with disbondment failure modes of certain coating systems. Over this testing period, the polysiloxane system appeared to hold up under these high potential conditions, which can be detrimental to coating systems that are more sensitive to CP. On day 135, a 6-inch defect was added near Anode 4, which needs to be re-examined at a later date to look for signs of cathodic disbondment. Future work with continued monitoring would help researchers better determine the response of the polysiloxane coating system in over-polarized conditions.

5. Conclusions

- The ribbon anode rings distributed CP current relatively evenly across the full immersed surface of the tank, even when using only one ribbon anode. This could be related to the coating quality of the newly coated tank, which had very few defects.
- The ON and instant-OFF potential showed greater IR drop in the tank-to-electrolyte measurements compared with the coupon measurements. This IR drop is expected to decrease as the coating develops more defects over time.
- The instant-OFF potential was more negative than desired (some measurements more negative than $-1100 \text{ mV}_{\text{CSE}}$), indicating that the ribbon anode system was over-designed for a newly coated tank. However, this presented an opportunity to observe how the polysiloxane coating system held up to the over-polarized CP current.
- The anode current density is very low (less than 1 mA/ft^2) and therefore the predominant method of anode consumption comes from self-corrosion. Longer term testing will allow for determination of the ribbon anode consumption rate.
- A visual inspection of the polysiloxane coating system revealed no issues 135 days into testing. Longer testing durations are needed to truly determine coating performance in immersion with CP applied.

6. Recommendations

- Recommend continued monitoring of the condition of the tank, ribbon anodes, and polysiloxane coating system in immersion. This will more accurately show how the CP and coating systems perform over a longer period of time.
- In future work, add intentional coating defects to simulate a coated tank that is further along in its service life. This will tax the CP and coatings system further and allow for additional observations regarding anode consumption, coupon vs. tank potential measurement comparisons, and polysiloxane performance as the coating deteriorates.
- When using ribbon anodes in field applications to protect tank interiors, designers should consider mitigation of over-polarization, as well as use of coating systems that are not sensitive to high levels of cathodic polarization.
- Over-polarization can be mitigated by reducing anode surface area through shielding techniques (e.g., bitumastic coating or electrical tape), or through current or potential control (e.g., variable resistors or auto-potential controllers). For field application of the ribbon anodes in a ring configuration, this method is recommended to be used in the following way:
 - Use an auto-potential controller to control anode potential and the number of anodes operating at a given time.
 - Use standard-potential magnesium ribbon anodes instead of high-potential magnesium ribbon anodes, if they become available.
 - Use a plastisol or bitumastic coating behind the area where the anode would be mounted or contain the anode in perforated conduit to protect the structure from over-polarization at these locations.
 - As tank height increases, additional anodes can be added up the wall to account for the increased surface area. But as tank diameter increases, an anode in the center of the tank may be required if the diameter becomes large enough to surpass the current discharge zone of the ribbon anode.
 - If there is a mixer or other centralized equipment at the center of the tank, consider using a small ribbon anode surrounding the center. This has not been tested in the lab but could be a good way to provide additional protection in the center of the tank.

Supporting Data Sets

Additional files associated with this project can be accessed as described below:

- File path: T:\Jobs\DO_NonFeature\Science and Technology\2020-PRG-Tank Cathodic Protection
- Point of Contact: Chrissy Henderson, chenderson@usbr.gov, 303-445-2348
- Short description of the data: Files primarily include cathodic protection design data, collected measurement data, data analysis, and photographs of experimental set-up and testing.
- Keywords: cathodic protection, corrosion, tanks, galvanic anode, ribbon anode, polysiloxane
- Approximate total size of all files: 270 Files, 20 Folders, 1.04 GB

References

- [1] W. von Baeckmann, W. Schwenk and W. Prinz, Handbook of Cathodic Corrosion Protection, Houston, TX: Gulf Publishing Company, 1997.
- [2] NACE SP0104, "The Use of Coupons for Cathodic Protection Monitoring Applications," NACE, Houston, TX, 2014.
- [3] SSPC-SP 10 /NACE No. 2, "Near-White Metal Blast Cleaning," NACE, Houston, TX, 2006.
- [4] NACE SP0188, "Discontinuity Holiday Testing for new Protective Coatings on Conductive Substrate," NACE, Houston, TX, 2006.
- [5] "NACE CP 3 Cathodic Protection Technologist Course Manual Version 1.01.01," NACE, Houston, TX, 2005.
- [6] NACE SP0169, "Control of External Corrosion on Underground or Submerged Metallic Piping Systems," NACE, Houston, TX, 2013.
- [7] NACE/ASTM G193-12d, "Standard Terminology and Acronyms Relating to Corrosion," ASTM International, West Conshohocken, PA, 2016.
- [8] A. Peabody, Control of Pipeline Corrosion, 2nd ed., Houston, TX: NACE, 2001.
- [9] ASTM D1654, "Standard Test Method for Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments," ASTM International, West Conshohocken, PA, 2016.
- [10] ASTM D610, "Standard Practice for Evaluating Degree of Rusting on Painted Steel Surfaces," ASTM International, West Conshohocken, PA, 2019.
- [11] ASTM D661, "Standard Test Method for Evaluating Degree of Cracking of Exterior Paints," ASTM International, West Conshohocken, PA, 2019.
- [12] ASTM D660, "Standard Test Method for Evaluating Degree of Checking of Exterior Paints," ASTM International, West Conshohocken, PA, 2019.
- [13] ASTM G8, "Standard Test Methods for Cathodic Disbonding of Pipeline Coatings," ASTM International, West Conshohocken, PA, 2019.

- [14] ASTM D714, "Standard Test Method for Evaluating Degree of Blistering of Paints," ASTM International, West Conshohocken, PA, 2017.
- [15] NACE SP0196, "Galvanic Anode Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage tanks," NACE, Houston, TX, 2015.
- [16] R. A. Gummow and S. M. Segall, "PRCI Contract PR-262-9736, In-Situ Evaluation of Directional Drill/Bore Coating Quality- Evaluation of Test Methods, Final Report," Oct 1998.
- [17] "NACE CP 4 Cathodic Protection Specialist Course Manual," NACE, Houston, TX, 2000.

Appendix A—Tank Preparation and Coating QA/QC

QA/QC was performed during preparation and coating of tank half 1 to ensure that manufacturer recommendations were being met. Tank half 2 followed the same construction steps, so the assumption can be made that the same requirements were met. A diagram showing location naming convention for QA/QC measurements is included in Figure A-1.

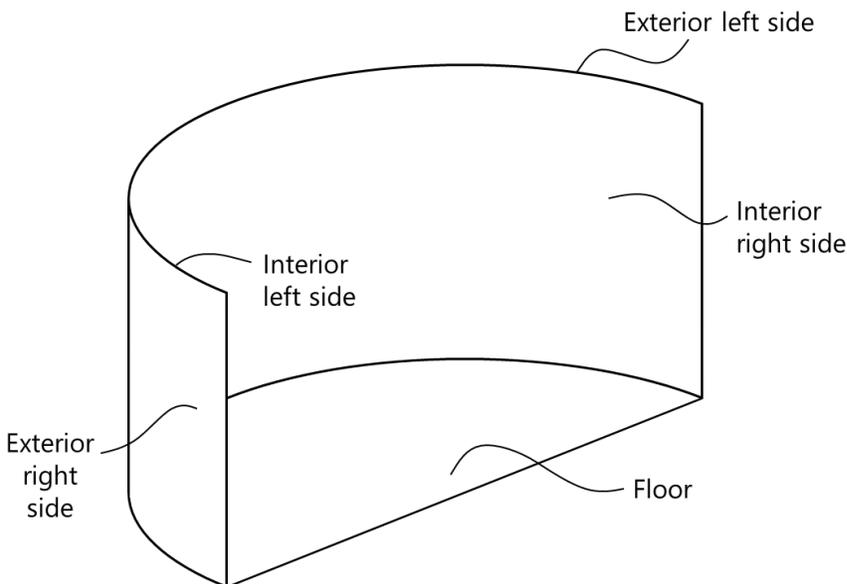


Figure A-1.— Diagram showing naming convention for tank half 1 for QA/QC measurements.

Surface Profile

After abrasive blasting, surface profile measurements were made using both replica tape (coarse and x-coarse) and a surface profile gauge. For the gauge, three measurements were taken at each location, following best practices. All measurements are included below in Tables A-1 and A-2.

Table A-1.— Tank Surface Profile Measurements using Replica Tape

Location	HT Coarse (mils)	HT X-Coarse (mils)
Floor	2.2	2.6
Interior right side	2.5	3.1
Interior left side	2.5	3.2
Exterior right side	2.1	2.2
Exterior left side	2.0	2.9

Table A-2.— Tank Surface Profile Measurements using a Surface Profile Gauge

Location	Measurement 1 (mils)	Measurement 2 (mils)	Measurement 3 (mils)
Floor	1.1	1.2	1.1
Interior right side	2.4	2.8	2.9
Interior left side	1.6	1	1.9
Exterior right side	0.8	0.5	0.5
Exterior left side	1.2	1.1	1.3

Environmentals

Environmental readings were made prior to each spray application to ensure that the manufacturer recommendations were being met. These readings are listed in Table A-3. All measurements were taken using a dew point meter probe.

Table A-3.— Environmental Readings during Tank Coating Application.

Measurement Taken	Date	Time	T _a (°F)	T _s (°F)	T _d (°F)	T _s - T _d (°F)	% RH	Comments
Week before Coat 1	7/2/20	10:00 AM	92.1*	107.1*	45.5	61.2	20.4	*The coating system has a 1-hour pot life at these ambient temperatures.
Week before Coat 1	7/2/20	10:40 AM	99.7*	113.2**	---	65.5	---	**The maximum steel temperature for this coating system is 120°F. Approaching temperature too hot to coat, so first coating application postponed to the following week.
Prior to Coat 1	7/6/20	6:12 AM	71.2	63.3	45.3	18.0	39.5	
Prior to Coat 2	7/7/20	6:30 AM	74.9	68.8	44.1	24.8	33.3	
Prior to Coat 3 (interior only)	7/8/20	---	---	---	---	---	---	Similar conditions to previous day, measurements not recorded.

Note: T_a=ambient temperature, T_s=surface temperature, T_d=dew point temperature, % RH=percent relative humidity.

For the first two weeks that environmental readings were taken, temperatures within the containment were too high for the coating application. Because of this, the coating application was postponed to the following week and performed earlier in the morning while temperatures within the containment were lower.

Dry Film Thickness

Dry film thickness (DFT) measurements were taken after each coat had fully cured using a DFT gauge. Prior to measurements, a 2-point calibration was performed with plastic shims. Measurement locations use the same notation listed in Figure A-1, as well as further dividing each location into top and bottom, or left middle and right thirds for the floor measurements.

A total of five DFT measurements were taken at each location and then averaged, following best practices. Measurements for the first coat are included in Table A-4 and measurements for the second coat are included in Table A-5.

Table A-4.—Dry Film Thickness (DFT) of First Coat, Measured 7/7/20

Location	DFT 1 (mils)	DFT 2 (mils)	DFT 3 (mils)	DFT 4 (mils)	DFT 5 (mils)	Avg DFT
exterior top left	3.1	3.7	2.7	3.0	3.0	3.1
exterior bottom left	3.4	3.9	3.4	3.8	3.3	3.6
exterior top middle	2.4	2.9	2.5	3.0	2.5	2.7
exterior bottom middle	3.8	4.1	4.1	3.8	3.7	3.9
exterior top right	4.1	4.0	4.0	4.3	3.9	4.1
exterior bottom right	3.4	3.5	3.8	3.7	3.6	3.6
interior top left	2.3	2.2	2.4	1.9	2.3	2.2
interior bottom left	2.9	3.1	3.3	3.8	4.1	3.4
interior top middle	2.6	3.2	2.3	2.9	3.3	2.9
interior bottom middle	3.5	3.3	3.7	3.3	3.7	3.5
interior top right	4.1	3.9	4.4	4.9	4.3	4.3
interior bottom right	3.8	4.2	4.2	4.2	4.0	4.1
floor left	3.3	3.1	3.2	3.2	3.7	3.3
floor middle	4.3	4.6	3.6	4.6	3.6	4.1
floor right	3.5	3.9	3.7	3.6	3.9	3.7
Average DFT:	3.4	3.6	3.4	3.6	3.5	3.5

Table A-53.—Dry Film Thickness (DFT) of Second Coat, Measured 7/8/20

Location	DFT 1 (mils)	DFT 2 (mils)	DFT 3 (mils)	DFT 4 (mils)	DFT 5 (mils)	Avg DFT
exterior top left	6.6	7.0	6.9	6.9	6.3	6.7
exterior bottom left	9.0	8.1	8.8	5.8	7.5	7.8
exterior top middle	9.0	7.9	8.2	7.7	8.1	8.2
exterior bottom middle	6.5	7.3	7.1	6.6	7.9	7.1
exterior top right	7.9	8.5	7.2	9.0	8.2	8.2
exterior bottom right	7.5	7.7	8.4	7.0	6.5	7.4
interior top left	8.1	7.3	8.0	7.9	8.3	7.9
interior bottom left	6.1	6.0	6.8	5.8	6.3	6.2
interior top middle	6.1	8.4	9.0	6.8	8.1	7.7
interior bottom middle	7.1	6.7	6.7	7.0	7.5	7.0
interior top right	7.2	6.5	8.0	7.7	6.5	7.2
interior bottom right	5.3	5.9	5.6	6.0	6.1	5.8
floor left	4.4	4.9	5.1	4.6	4.6	4.7
floor middle	8.5	8.8	9.1	8.4	8.5	8.7
floor right	6.4	5.7	7.2	6.5	7.1	6.6
Average DFT:	7.0	7.1	7.5	6.9	7.2	7.1

Appendix B—Cathodic Protection Test Data

Tank-to-Electrolyte Measurements

Table B-1.—Tank-to-Electrolyte Potential Measurements for Test 1, All Anodes On

Date	Days into Test	Cumu. Days	R1 ON (-mV _{CSE})	R1 OFF (-mV _{CSE})	R2 ON (-mV _{CSE})	R2 OFF (-mV _{CSE})	R3 ON (-mV _{CSE})	R3 OFF (-mV _{CSE})	R4 ON (-mV _{CSE})	R4 OFF (-mV _{CSE})	R5 ON (-mV _{CSE})	R5 OFF (-mV _{CSE})	R6 ON (-mV _{CSE})	R6 OFF (-mV _{CSE})
10/7/21	0	0	---	869	---	869	---	867	---	870	---	869	---	860
1/12/22	67	67	1508	1060	1517	1088	1511	1086	1507	1094	1505	1097	1502	1088
1/18/22	97	97	1488	1084	1492	1099	1487	1092	1484	1072	1481	1068	1479	1078
1/26/21	111	111	1484	1063	1488	1063	1482	1076	1479	1083	1478	1076	1476	1052

Note: highlighted row (date 10/7/21) contains native potentials.

Table B-2.—Tank-to-Electrolyte Potential Measurements for Test 2, Anode 1 On

Date	Days into Test	Cumu. Days	R1 ON (-mV _{CSE})	R1 OFF (-mV _{CSE})	R2 ON (-mV _{CSE})	R2 OFF (-mV _{CSE})	R3 ON (-mV _{CSE})	R3 OFF (-mV _{CSE})	R4 ON (-mV _{CSE})	R4 OFF (-mV _{CSE})	R5 ON (-mV _{CSE})	R5 OFF (-mV _{CSE})	R6 ON (-mV _{CSE})	R6 OFF (-mV _{CSE})
2/4/22	0	111	1471	1081	1470	1096	1466	1083	1465	1081	1462	1093	1460	1096
2/18/22	14	125	1475	1086	1475	1093	1471	1083	1469	1079	1466	1086	1465	1091
2/28/22	24	135	1477	1080	1477	1092	1474	1090	1472	1090	1468	1086	1466	1080

Table B-3.—Tank-to-Electrolyte Potential Measurements for Test 3, All Anodes On

Date	Days into Test	Cumu. Days	R1 ON (-mV _{CSE})	R1 OFF (-mV _{CSE})	R2 ON (-mV _{CSE})	R2 OFF (-mV _{CSE})	R3 ON (-mV _{CSE})	R3 OFF (-mV _{CSE})	R4 ON (-mV _{CSE})	R4 OFF (-mV _{CSE})	R5 ON (-mV _{CSE})	R5 OFF (-mV _{CSE})	R6 ON (-mV _{CSE})	R6 OFF (-mV _{CSE})
6/9/22	0	135	---	---	---	---	---	---	---	---	---	---	---	---
6/14/22	5	140	1423	1106	1460	1108	1458	1098	1458	1096	1408	1090	1448	1073
7/5/22	26	161	1446	1081	1427	1042	1453	1080	1431	1090	1449	1071	1422	1070
7/19/22	40	175	1423	1048	1448	1083	1440	1081	1446	1072	1409	1062	1445	1076
7/27/22	48	183	1425	1046	1445	1062	1437	1056	1442	1081	1410	1041	1442	1076

Note: the tank was dewatered prior to beginning Test 3.

Table B-4.—Tank-to-Electrolyte Potential Measurements for Test 4, Anode 4 On

Date	Days into Test	Cumu. Days	R1 ON (-mV _{CSE})	R1 OFF (-mV _{CSE})	R2 ON (-mV _{CSE})	R2 OFF (-mV _{CSE})	R3 ON (-mV _{CSE})	R3 OFF (-mV _{CSE})	R4 ON (-mV _{CSE})	R4 OFF (-mV _{CSE})	R5 ON (-mV _{CSE})	R5 OFF (-mV _{CSE})	R6 ON (-mV _{CSE})	R6 OFF (-mV _{CSE})
7/27/22	0	183	---	---	---	---	---	---	---	---	---	---	---	---
8/12/22	16	199	1439	1101	1453	1106	1433	1119	1441	1112	1400	1112	1450	1113
8/25/22	29	212	1410	1108	1448	1110	1437	1104	1436	1092	1418	1108	1439	1102
9/7/22	42	225	1413	1122	1456	1113	1435	1101	1440	1104	1418	1102	1437	1105
9/20/22	55	238	1417	1105	1455	1111	1433	1102	1440	1103	1426	1103	1445	1102

Table B-5.—Tank-to-Electrolyte Measurements: Average Values for All Reference Electrodes Across All Tests

Measurement	Value (mV _{CSE})*	Standard Deviation (mV _{CSE})*
Native Potential	-867	3.72
IR Drop	382.2	5.88
OFF Potential	-1073	2.59

*Note that units are positive mV_{CSE} and not negative (-)mV_{CSE} as in the previous tables.

Coupon Measurements

Table B-6.—Coupon Potential Measurements for Test 1, All Anodes On

Date	Days into Test	Cumu. Days	C1 ON (-mV _{CSE})	C1 OFF (-mV _{CSE})	C2 ON (-mV _{CSE})	C2 OFF (-mV _{CSE})	C3 ON (-mV _{CSE})	C3 OFF (-mV _{CSE})	C4 ON (-mV _{CSE})	C4 OFF (-mV _{CSE})	C5 ON (-mV _{CSE})	C5 OFF (-mV _{CSE})	C6 ON (-mV _{CSE})	C6 OFF (-mV _{CSE})
10/7/21	0	0	---	-678	---	-678	---	-678	---	-680	---	-679	---	-668
10/7/21	0	0	1503	1083	1618	1238	1607	1407	1606	1166	1581	1191	1604	1314
10/13/21	6	6	1599	1203	1587	1208	1576	1188	1560	1163	1565	1189	1566	1183
10/26/21	19	19	1513	1119	1529	1159	1525	1175	1522	1133	1519	1155	1519	1176
11/16/21	40	40	1516	1010	1522	1111	1517	1132	1515	1098	1514	1144	1509	1170
12/1/21	55	55	1515	1234	1518	1134	1515	1143	1511	1129	1510	1149	1498	1179
1/12/22	67	67	1508	1120	1517	1118	1511	1111	1507	1097	1505	1136	1502	1160
1/18/22	97	97	1488	1228	1492	1116	1487	1085	1484	1102	1481	1142	1479	1152
1/26/21	111	111	1485	1102	1488	1111	1483	1090	1480	1103	1478	1131	1477	1148

Note: highlighted row (date 10/7/21) contains native potentials.

Table B-7.—Coupon Potential Measurements for Test 2, Anode 1 On

Date	Days into Test	Cumu. Days	C1 ON (-mV _{CSE})	C1 OFF (-mV _{CSE})	C2 ON (-mV _{CSE})	C2 OFF (-mV _{CSE})	C3 ON (-mV _{CSE})	C3 OFF (-mV _{CSE})	C4 ON (-mV _{CSE})	C4 OFF (-mV _{CSE})	C5 ON (-mV _{CSE})	C5 OFF (-mV _{CSE})	C6 ON (-mV _{CSE})	C6 OFF (-mV _{CSE})
2/4/22	0	111	1470	1096	1471	1096	1467	1081	1465	1090	1462	1103	1461	1132
2/18/22	14	125	1474	1094	1475	1096	1473	1086	1470	1090	1467	1121	1464	1130
2/28/22	24	135	1476	1096	1478	1090	1474	1076	1472	1091	1469	1110	1468	1130

Table B-8.—Coupon Potential Measurements for Test 3, All Anodes On

Date	Days into Test	Cumu. Days	C1 ON (-mV _{CSE})	C1 OFF (-mV _{CSE})	C2 ON (-mV _{CSE})	C2 OFF (-mV _{CSE})	C3 ON (-mV _{CSE})	C3 OFF (-mV _{CSE})	C4 ON (-mV _{CSE})	C4 OFF (-mV _{CSE})	C5 ON (-mV _{CSE})	C5 OFF (-mV _{CSE})	C6 ON (-mV _{CSE})	C6 OFF (-mV _{CSE})
6/9/22	0	135	---	---	---	---	---	---	---	---	---	---	---	---
6/14/22	5	140	1439	1138	1461	1129	1436	1122	1462	1116	1419	1152	1455	1131
7/5/22	26	161	1428	1123	1451	1110	1441	1073	1447	1091	1422	1125	1448	1130
7/19/22	40	175	1420	1136	1451	1108	1443	1083	1450	1090	1407	1112	1445	1112
7/27/22	48	183	1424	1120	1448	1136	1436	1108	1449	1096	1411	1112	1442	1121

Note: the tank was dewatered prior to beginning Test 3.

Table B-9.—Coupon Potential Measurements for Test 4, Anode 4 On

Date	Days into Test	Cumu. Days	C1 ON (-mV _{CSE})	C1 OFF (-mV _{CSE})	C2 ON (-mV _{CSE})	C2 OFF (-mV _{CSE})	C3 ON (-mV _{CSE})	C3 OFF (-mV _{CSE})	C4 ON (-mV _{CSE})	C4 OFF (-mV _{CSE})	C5 ON (-mV _{CSE})	C5 OFF (-mV _{CSE})	C6 ON (-mV _{CSE})	C6 OFF (-mV _{CSE})
7/27/22	0	183	---	---	---	---	---	---	---	---	---	---	---	---
8/12/22	16	199	1438	1113	1451	1110	1435	1152	1432	1093	1401	1122	1447	1123
8/25/22	29	212	1409	1120	1450	1112	1450	1090	1437	1097	1414	1120	1435	1130
9/7/22	42	225	1406	1124	1454	1103	1434	1081	1416	1086	1418	1111	1438	1146
9/20/22	55	238	1408	1109	1451	1110	1436	1098	1431	1089	1430	1114	1447	1131

Table B-10.—Coupon Measurements: Average Values for All Coupons Across All Tests

Measurement	Value (mV _{CSE})	Standard Deviation (mV _{CSE})
Native Potential	-677	4.40
IR Drop	349.7	18.08
OFF Potential	-1128	15.05

*Note that units are positive mV_{CSE} and not negative (-)mV_{CSE} as in the previous tables.

Anode Outputs

Table B-11.—Anode Output Measurements for Test 1, All Anodes On

Date	Days into Test	Cumulative Days	Anode 1 Output (mA)	Anode 2 Output (mA)	Anode 3 Output (mA)	Anode 4 Output (mA)
1/12/22	67	67	0.3	0.2	0.1	0.3
1/18/22	97	97	0.3	1.1	0	0.2
1/26/21	111	111	0.2	1.15	0	0.3

Table B-12.—Anode Output Measurements for Test 2, Anode 1 On

Date	Days into Test	Cumulative Days	Anode 1 Output (mA)	Anode 2 Output (mA)	Anode 3 Output (mA)	Anode 4 Output (mA)
2/4/22	0	111	1	0	0	0
2/18/22	14	125	1.3	0	0	0
2/28/22	24	135	1.2	0	0	0

Table B-13.—Anode Output Measurements for Test 3, All Anodes On

Date	Days into Test	Cumulative Days	Anode 1 Output (mA)	Anode 2 Output (mA)	Anode 3 Output (mA)	Anode 4 Output (mA)
6/9/22	0	135	0.3	0.2	0.2	1
6/14/22	5	140	0.7	0.4	0.4	1.8
7/5/22	26	161	0.5	0.25	0	1.6
7/19/22	40	175	0.5	0.2	0	1.4
7/27/22	48	183	0.5	0.2	0	1.3

Note: the tank was dewatered prior to beginning Test 3.

Table B-14.—Anode Output Measurements for Test 4, Anode 4 On

Date	Days into Test	Cumulative Days	Anode 1 Output (mA)	Anode 2 Output (mA)	Anode 3 Output (mA)	Anode 4 Output (mA)
7/27/22	0	183	---	---	---	---
8/12/22	16	199	0	0	0	1.5
8/25/22	29	228	0	0	0	1.5
9/7/22	42	270	0	0	0	1.5
9/20/22	55	325	0	0	0	1.5