Immersed Hydraulic Steel Structure Corrosion Protection – Rust Busters Prize Competition

Denver, CO

U.S. Department of the Interior December 2021

Immersed Hydraulic Steel Structure Corrosion Protection – Rust Busters Prize Competition

Christine Henderson, Ph.D., P.E.
Grace Weber
Stephanie Prochaska
Allen Skaja, Ph.D., PCS
Mack Cleveland
Bobbi Jo Merten, Ph.D., PCS

Abstract

The research and development of new technologies continues to be an important objective for government agencies, utilities, and the private sector to combat the rising costs of corrosion protection for immersed water infrastructure. This paper shares the approach and initial outcomes of the Rust Busters prize competition, sponsored by the Bureau of Reclamation and an international crowdsourcing administrator. The prize competition sought to extend the life of corrosion protection systems for water infrastructure, focusing on gates and penstock interiors. Participants from around the world and across many technical disciplines submitted a white paper solution description during the initial phase. A panel of subject matter experts evaluated the submissions based on established criteria and recommended five submissions to advance for prototype development, delivery, and laboratory and field evaluation. The five advancing submissions included four protective coatings solutions and one novel approach to cathodic protection. This paper details the Rust Busters prize competition design and laboratory testing results for the protective coatings solutions.

Introduction

The Bureau of Reclamation is the largest provider of water in the country and the second largest producer of hydroelectric power. There are numerous hydraulic steel structures (HSS) in Reclamation's dams and power plants, and the most prominent HSS are gates and penstocks. Penstocks are pipes that carry water from upstream reservoirs to the hydroelectric turbines. Gates are the water control structures in penstocks, reservoirs, and other waterways.

The standard corrosion protection approaches for HSS are protective coatings and cathodic protection. Protective coatings are the first line of defense against the corrosion of steel structures. The original coatings for these structures were coal tar enamel and solution vinyl coatings, which provide superior protection for hydraulic structures. But their use is now limited due to health, safety, and environmental concerns. Cathodic protection systems are typically used in conjunction with coatings. These systems prevent corrosion by making the steel structure a cathode in an electrochemical circuit. Cathodic protection works for gates only while they are in the water and may not provide adequate protection in the high-flow conditions of penstocks.

To address rising maintenance costs and to advance the state of the art for corrosion control, the Bureau of Reclamation (Reclamation) sponsored a two-phase Rust Busters prize competition. The prize competition included prototype development and evaluation phases and is a follow-on to the 2017 white-paper prize competition, "Long-Term Corrosion Protection of Existing Hydraulic Steel Structures [1]." Both competitions sought to identify and develop new methods for corrosion control. Approaches to minimize down time, reduce or eliminate direct human operation, or lower the frequency of maintenance or replacement were of interest. Reclamation and its partners are vitally interested in approaches that were outside of conventional thought for corrosion control and that could be applied to existing structures in situ.

Background

The Rust Busters prize competition offered the opportunity for novel or innovative corrosion control approaches to be evaluated and field-tested by Reclamation and its partner, the U.S. Army Corps of Engineers. In Phase 1, participants submitted a paper containing the proposed approach to corrosion control, its scientific rationale, and any supporting data. Five of the most compelling submissions were selected as Phase 1 winners. The five Phase 1 winners were given the opportunity to participate in Phase 2 and received a cash prize. For the Phase 2 development, participants were asked to apply their technologies to provide corrosion protection on supplied test coupons and steel samples for lab and field evaluation, respectively.

The prize competition solutions could be a completely new idea or a new, safer, or more efficient way to apply a known technology. Solutions that demonstrated technical maturity, e.g., likelihood that proposed approach can be demonstrable within the 6-month development period, could be applied to existing structures in situ, and could be applied under standard maintenance conditions were ideal. The specific technical requirements of the prize competition were as follows [2]:

- Offer durability to abrasion and impacts from objects and sediment in fast flowing water that meets or exceeds current protection systems
- Provide service life of 50 or more years (yrs) at an approximate cost no more than $540/m^2 per 50 yrs ($50/ft^2 per 50 yrs)
- Require regular maintenance such that the cost and frequency of such maintenance is on par with or less than current maintenance costs, which are on the order of $100/m^2 per 15 yrs ($10/ft^2 per 15 yrs)
- Be applicable to either existing penstocks or gates in situ, including structures which have complex and irregular geometries - including multiple edges, rivets, and welds
- Use materials or techniques that are safe for humans to apply and are environmentally safe, in service conditions

At the completion of Phase 1, a team of subject matter experts evaluated the degree to which each submission accomplished the technical requirements. The submissions were evaluated based on strength of the approach, soundness of reasoning, any preliminary data, completeness of responses, feasibility, and innovation. The following five solutions were selected to advance to Phase 2 for prototype development, delivery, and evaluation:

- *Ceramic Rust Universal Sealant Technology*. The solution is a chemically bonded phosphate ceramic coating to increase corrosion protection through enhanced substrate bonding.
- *High Barrier Controlled Release Rustbuster Coating*. The solution is a modified polysulfide coating with organometallo-phosphato polymer to improve barrier protection.
- *New Method for Kathodic Protection*. The solution is a self-powered thermal gradient cathodic protection system.
- *Novel Sol Gel for Advanced Corrosion Protection*. The solution is a flexible hydrophobic topcoat to improve barrier protection.
- *Coal Tar Enamel Spray*. The solution provides the equipment and method for robotic spray application of coal tar enamel so that workers need not be present in the application environment.

Materials and Methods

Materials

Three types of 0.32 cm (1/8-inch) thick test coupons were used for laboratory testing: 28 cm (11-inch) A36 steel disc, 10.3 cm (4-inch) discs, and flat 7.75 cm x 15.5 cm (3-inch x 6-inch) rectangular panels. Surface preparation entailed removal of oil and contaminants by solvent cleaning with a detergent by SSPC-SP1 [3], rinsing with water, and immediately drying with paper towels. Test coupons were abrasive blasted to SSPC-SP 5/NACE 1 with an angular profile of 63.5 µm (2.5 mils) [4].

Test coupons were packaged in rust preventative paper, shipped to participants, and returned with solutions applied. Table 1 provides the name designations, solution description, and dry film thickness. Systems F and G are experimental controls of coatings currently used in the field and were prepared and applied in accordance with manufacturer instructions.

Table 1: Letter designation for competition samples and experimental controls.

System	Description of Corrosion Protection System	Average Dry Film Thickness ± One Standard Deviation, µm (mils)
A	Phosphate ceramic coating	356 ± 46 (14 ± 1.8)
B	Sol gel with hydrophobic top coat	102 ± 25 (4 ± 1.0)
C	Polysulfide coating with organometallo-phosphato polymer	686 ± 140 (27 ± 5.5)
D	Robotic spray application of coal tar enamel	686 ± 89 (27 ± 3.5)
E	Self-powered thermal cathodic protection	N/A
F	USACE System 5-EZ zinc rich vinyl primer and 4 coats of vinyl	305 ± 23 (12 ± 0.9)
G	Zinc rich epoxy primer and two coats of an epoxy polysiloxane	432 ± 3 (17 ± 0.1)

Methods

Table 2 provides the Phase 2 laboratory evaluation approach for the Phase 1 winner prototypes and the number of replicates for each test. The full evaluation was applied to Systems A-D, F and G, unless otherwise noted, while the cathodic protection solution (System E) was evaluated directly for its corrosion protection performance via NACE SP0169 [5]. System E testing results will not be included in this paper.

Table 2. Laboratory performance testing approach for coating systems.

Test Name	Test Method	Replicates
Corrosion Testing: Immersion (DI)	ASTM D870/ ASTM D1654 [6] [7]	3
Corrosion Testing: Immersion (HAR)	ASTM D870/ ASTM D1654 [6] [7]	3
Corrosion Testing: Cyclic Prohesion (PRO)	ASTM D5894/ ASTM D1654 [8] [7]	3
Corrosion Testing: Cyclic Prohesion + Immersion (BOR)	ASTM D5894/ ASTM D1654 [7]	3
Corrosion Testing: Coating barrier properties	Electrochemical impedance spectroscopy	1
Physical Testing: Cathodic Disbondment	NACE TM0115 [9]	3
Physical Testing: Erosion Resistance	USBR-5071-2015	2
Physical Testing: Abrasion Resistance	ASTM D4060 [10]	4
Physical Testing: Impact resistance	ASTM D2794 [11]	1
Physical Testing: Pull-off adhesion (dry and wet)	ASTM D4541 [12]	3
Physical Testing: Knife adhesion	ASTM D6677 [13]	3

Corrosion Testing

Water immersion testing consisted of evaluation in two solutions in accordance with ASTM D870 [6]. Testing occurred at room temperature of 21-24 Celsius (70-75 Fahrenheit). Deionized water (DI) testing used 1-Megaohm resistance water. Dilute Harrison solution (HAR) testing comprised of DI with 0.5 weight percent (wt.%) sodium chloride (NaCl) and 3.5 wt.% ammonium sulfate ($(NH_4)_2SO_4$,).

Cyclic testing consisted of two testing procedures. Systems A-C, F, and G followed ASTM D5894 prohesion testing (PRO), consisting of one week in a UV weathering chamber per ASTM D4587 method B (QUV) and one week in a fog cabinet per ASTM G85 Annex 5 (FOG) [8] [14] [15]. The BOR testing procedure followed a four-week rotating cycle of QUV, FOG, HAR, and FOG. The BOR procedure is unique to the Bureau of Reclamation and combines water immersion and cyclic testing [8].

System D was not tested in the QUV chamber, because coal tar enamel can only be used in areas with no UV exposure. The cyclic testing instead consisted of constant (FOG) ASTM G85 annex 5 for the first set and a rotation of one week in FOG and one week in HAR (HAR/FOG) for the second set [15].

Prior to water immersion and cyclic testing, test coupons received a scribe through the coating to the substrate. The exception is one test coupon from each water immersion set in order to use it for electrochemical impedance spectroscopy (EIS) testing.

Corrosion undercutting was evaluated in accordance with ASTM D1654 follows 5040 hours of water immersion and cyclic testing [7]. The testing used Procedure A Method 2, scraping after exposure. The width of the corrosion undercutting was measured randomly in 8 locations. The width was divided by two and subtracted by the original scribe width to determine the average distance of corrosion undercutting.

EIS was used to evaluate the barrier properties of one DI and one HAR test coupon per system for 30 weeks. Initial EIS testing occurred weekly to bi-weekly for the first eight weeks and was then extended to every four weeks through remaining evaluation period. The test parameters for EIS measurements were a 10-millivolt (mV) sinusoidal perturbation at the open circuit potential, a frequency range of 10^5 to 10^{-2} Hertz (Hz), and ten data points per decade. The EIS test cell was consistent with a three-electrode set-up, using a saturated calomel electrode (SCE), platinum mesh electrode, and the steel substrate connected to a Gamry Femtostat FAS2 as the reference, counter, and working electrode, respectively. The EIS testing surface area, as defined by the test cell, is 23 square cm (cm^2), and the raw data was not adjusted for surface area in the analysis and reporting.

Physical Testing

Cathodic disbondment (CD) testing evaluated the suitability for use with cathodic protection. CD testing is an accelerated test that uses an external power source to apply a specified polarization potential on the test coupon. At the end of the test period, the disbondment is measured and the tested coating systems are ranked by performance. For this work, CD testing was performed following standard test method NACE TM0115 with the modification described below [9].

Three 7.6 x 15.2 x 0.3 cm (3- x 6- x 1/8-inch) test coupons from each coating system were used for CD testing for a period of 31 days. These test coupons do not meet the minimum size requirements of NACE TM0115. However, an appropriately sized polyvinyl chloride test cell was able to be adhered to each coupon using silicone sealant and adhesive. Each test cell was checked for leaks prior to testing, and additional sealant was applied if needed.

As required by NACE TM0115, specimens were holiday tested with a low-voltage wet sponge by NACE SP0188 [16]. All System B-D, F, and G specimens passed holiday testing. All System A specimens failed holiday testing.

The Taber abrasion test follows ASTM D4060 test method using a 1000 gram (g) weight and CS-17 wheel [10]. The weight loss is measured to the nearest 0.1 milligrams (mg). The test used 10.16 cm (4-inch) disc with an 0.3 cm (1/8-inch) hole in the center. Four replicates were run to obtain an average and standard deviation.

The slurry erosion test used two 27.9 cm (11-inch) discs secured to the test apparatus by an anchor hole in the middle. The first disc was placed into a metal cylindrical container and secured to the bottom with a bolt. The cylindrical container was then filled with 16 liters of DI water and 1000 g of size 16 brown aluminum oxide abrasive. A Jiffy style paddle was attached to an electric motor and used to stir the water-abrasive mixture for 24 hours. The second disc was placed into a container of DI water and used as a control for the experiment. After 24 hours the plates were removed, cleaned, and dried using shop towels or rags. Once dried, both discs were weighed, and the coating material loss calculated as the difference between the two disc. Disc 1 was exposed to four 24-hour periods for a total of 96 hours of erosion testing. Disc 2 was left inside of the DI water container for 96 hours and removed every 24 hours to be weighed simultaneously with Disc 1.

The direct impact was measured using ASTM D2794 with a modification to thicker, 0.3 cm (1/8-inch) steel [11]. The steel thickness allowed for abrasive blast cleaning without warping the steel. The highest impact load that can be delivered in this set-up is 18 newton-meters (N-m)(160 inch-pounds (in-lbs)).

Wet and dry pull-off adhesion (ASTM D4541) and knife adhesion (ASTM D6677) quantitatively evaluated adhesion strength for each coating system [12] [13]. The dolly and coating surface were sanded with 80-grit sandpaper and cleaned. Three 20-millimeter (mm) diameter aluminum dollies were glued to the coating surface for the wet and dry pull off adhesion tests with a 31 megapascals (MPa) (4500 pounds per square inch (psi)) epoxy adhesive. The dollies were arranged to avoid edge effects and interference from other dollies. A circular tool was used to score the coating around each dolly [12]. A Type V adhesion tester applied a load rate of approximately 0.3 MPa (50 psi) per second to the dollies until they failed. The wet adhesion test conditioned the system in 100 percent (%) humidity for 24 hours while the epoxy glue cured and prior to pull off testing. Knife adhesion was performed with a utility knife on samples immediately following HAR exposure.

Results and Discussion

Corrosion Testing

Coatings were evaluated for corrosion protection by the extent of undercutting, blistering, cracking, and disbondment for each exposure condition. Table 3 shows the results for each coating system rated from 0-10. A rating of 10 indicates no undercutting or coating damage due to cracking or blistering, whereas a rating of 0 is extensive damage.

Table 3. ASTM D1654 undercutting results, as rated 0-10.

System	HAR	DI	PRO	BOR
A***	0	0	0	0
B	0*	0*	0*	4
C	8	7	0*	0*
D	8	9	2**	6**
F	9	10	5	5
G	10	10	8	7

**Assigned "0" rating due to blistered or cracked coating over entire surface.*

***System D could not be evaluated by same test procedure, the PRO was only FOG, and BOR was FOG and HAR immersion cycles.*

****System A was removed from testing after 4 weeks due to advanced coating degradation.*

System F and G are experimental controls and showed little degradation, particularly in immersion testing. System A was removed after four weeks of exposure due to advanced coating degradation; the coating was breaking apart into flakes and appeared to be dissolving into the solution. System B blistered in DI and HAR water immersion service beginning at 4 weeks of exposure and had blistering in PRO cyclic testing. The blisters grew larger with time. Systems A and B rated low according to ASTM D1654 and received results of zero, except for System B in BOR testing.

System C sustained minimal rust creep in water immersion testing. In BOR and PRO cyclic testing the system chalked severely and cracked at 4 weeks, progressing over time. For system C results of zero were obtained for both PRO and HAR cyclical tests. It appears alternating environments, such as what may be seen on gates that are raised in and out of the water, increased the degradation observed for System C. Penstock interiors are a more suitable environment for this system based on these testing results.

System D sustained minimal rust creep in water immersion testing. However, it did not perform as favorably under constant FOG. This suggests the coating system is more suited for immersion service with no cyclic changes to the environment. A coating such as this would perform well in penstocks but not on gates.

Electrochemical Impedance Spectroscopy

EIS results can be visualized using Bode diagrams of the impedance magnitude ($|Z|$) and phase angle verses frequency. For coated substrates, the low frequency, e.g., $|Z|$ at 0.01 Hz ($|Z|_{0.01}$), of above 10^8 ohms indicates the coating is providing excellent barrier protection [17]. For this evaluation, barrier protection is considered to be fair from 10^8 to 10^7 ohms and poor below 10^7 ohms. Phase angle at low frequencies indicate the resistive or capacitive behaviors of the coating system, where -90 degrees (deg) represents a pure capacitor and 0 deg is a pure resistor. Together, $|Z|$ and phase angles at low frequencies can be used to quantitatively describe the barrier properties of a coating system at a given time. Measurements of the same coating at multiple points in time can be used to study degradation of relevant properties.

System A provided poor initial results coupled with visible coating deterioration and was removed from the laboratory testing after the first and second weeks of testing for the HAR and DI coupons, respectively. The $|Z|_{0.1\ Hz}$ was approximately 10^3 ohms, and the phase angle was 0 deg at 0.01 Hz, indicating no barrier protection.

System B barrier properties increased during the first eight weeks of testing, with $|Z|_{0.01}$ of 3.7 x 10^6 ohms after five days of DI immersion and increasing to 1.1 x 10^7 ohms by week eight (T=8) and remaining above 10^7 ohms by the end of the 30 week evaluation period as shown in Figure 1 (top). Phase angles were resistive and approached 0 deg at approximately 0.1 Hz for each evaluation. Barrier properties for System B in HAR immersion decreased with increased time, and the impedance was generally lower than the DI counterparts (Figure 1, bottom). Although the initial measurement was 4.8 x 10^6 ohms, by the eighth week, the $|Z|_{0.01}$ had dropped to 2.4 x 10^6 ohms, and at 30 weeks $|Z|_{0.01}$ was 1.1 x 10^5 ohms. The phase angles for the HAR coupons also approached 0 deg at approximately 0.1 Hz for all test times.

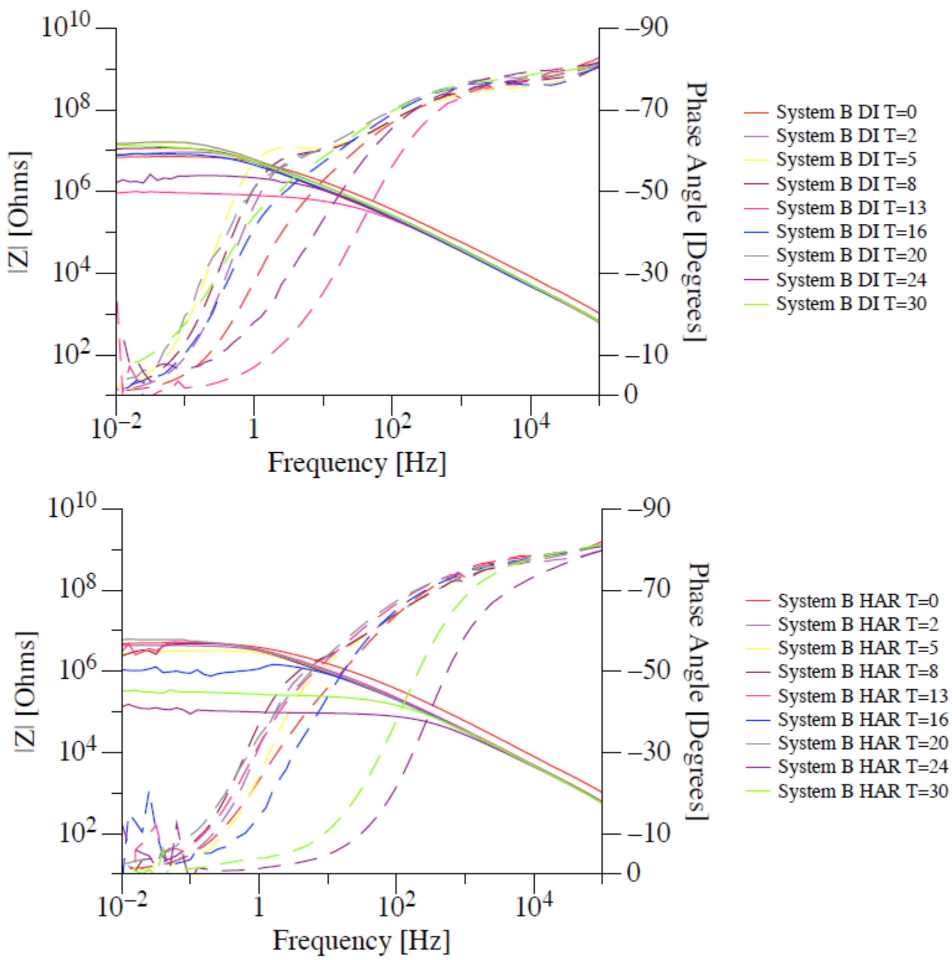

Figure 1: System B EIS results for DI immersion (top) and HAR immersion (bottom), where T equals weeks of exposure.

System C EIS results (not shown) were noisy at the low frequencies, but $|Z|_{0.01}$ averaged approximately 10^5 ohms for both DI and HAR immersion coupons, with barrier properties increasing throughout the evaluation period for DI coupons and decreasing with evaluation period for the HAR coupons. Phase angles for both the DI and HAR coupons fluctuated in the range of -20 and 0 deg. Overall the results indicated poor protection.

System D EIS results were also noisy at the low frequencies and $|Z|_{0.01}$ were spread across a large range with no clear correlation. For the DI coupon, the lowest $|Z|_{0.01}$, 10^5 ohms, was the initial measurement and the highest, 10^7 ohms, was after nearly four weeks in immersion. The initial $|Z|_{0.01}$ HAR coupon, at T=0, was nearly 10^{10} ohms but decreased to 3.1 x 10^6 ohms by the 30th week. Phase angles for both DI and HAR coupons showed resistive behavior ranging from 20 to 0 deg.

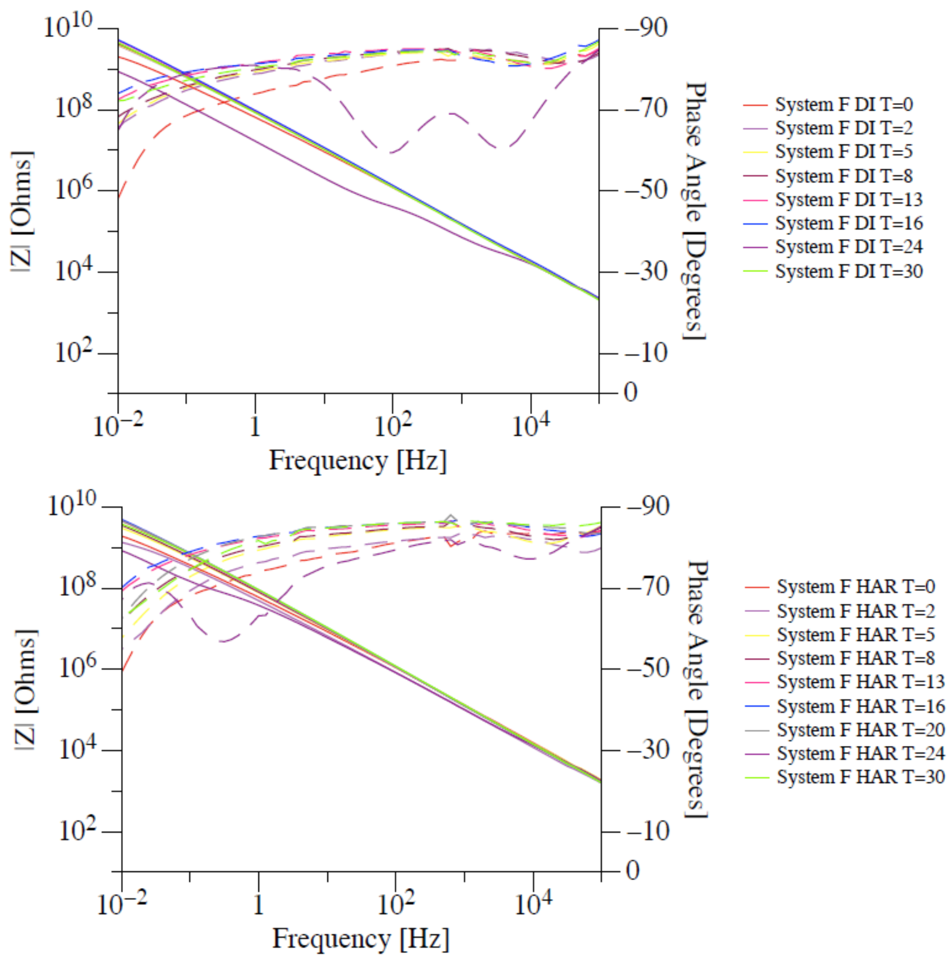

Figure 2: System F measured via EIS of all evaluated systems.

The EIS results for DI immersion for System F showed a clear correlation between $|Z|_{0.01}$ and immersion time. The initial $|Z|_{0.01}$, at T=0, was 2.0 x 10^9 ohms, and each subsequent EIS test showed increasing $|Z|_{0.01}$. The $|Z|_{0.01}$ at week eight was 4.2 x 10^9 ohms with little deviation throughout the remainder of the evaluation period (Figure 2, top). Correspondingly, phase angles became more negative (capacitive) with immersion time, increasing from -50 deg at the initial evaluation to approximately -70 deg at week 30. The System F HAR coupon showed similar behavior (Figure 2, right) and had a similarly high $|Z|_{0.01}$ after the 30-week immersion period. The phase angles were a few degrees more resistive than those of the DI coupons.

System G had the highest impedance magnitude measured via EIS of all systems evaluated and performed similarly to System F, with $|Z|_{0.01}$ of greater than 10^9 ohms for all evaluation times for both DI and HAR coupons. For both DI and HAR, the initial measurement at T=0 was most resistive with a phase angle near -20 deg. As immersion exposure progressed, the phase angles became more capacitive, approximately -50 deg and -40 deg for the DI and HAR coupons, respectively.

For the coating systems evaluated, the HAR immersion exposure generally resulted in lower $|Z|_{0.01}$ compared to the coupons in DI immersion exposure. Correspondingly, phase angles for HAR coupons were more positive, indicating more resistive behavior than the DI coupons. However, the differences were typically quite small.

Cathodic Disbondment

All three System A specimens failed holiday testing and were unable to maintain required polarization levels during cathodic disbondment testing. Therefore, cathodic disbondment testing was not performed on System A. All three System B specimens blistered across the entire test cell surface area during the testing period and were no longer able to maintain required polarization levels. As a result, the System B test was ended early and all specimens were determined to have disbonded across the entire test cell area, giving a maximum disbondment value of 3.493 cm (1.375 inches). Average disbondment values for each coating system are shown in Figure 3.

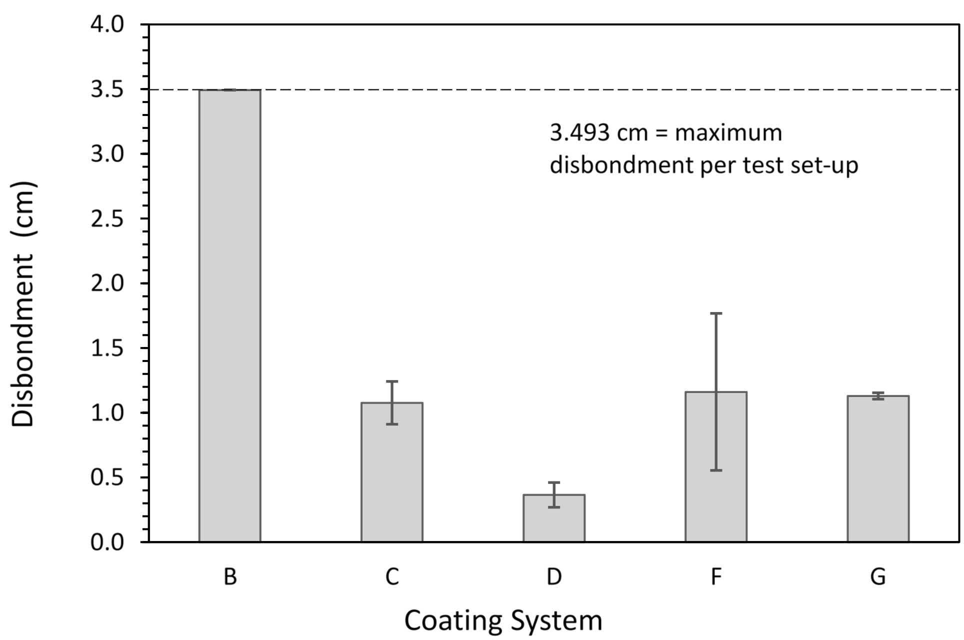

Figure 3: Average disbondment value for each coating system.

System D had the lowest average disbondment value at 0.366 cm (0.144 inches). Systems C, F, and G had similar levels of disbondment. System F had a high standard deviation, indicating that additional replicates must be tested to verify the disbondment value for this coating system. Photographs of a representative specimen from each coating system are shown in Figure 4.

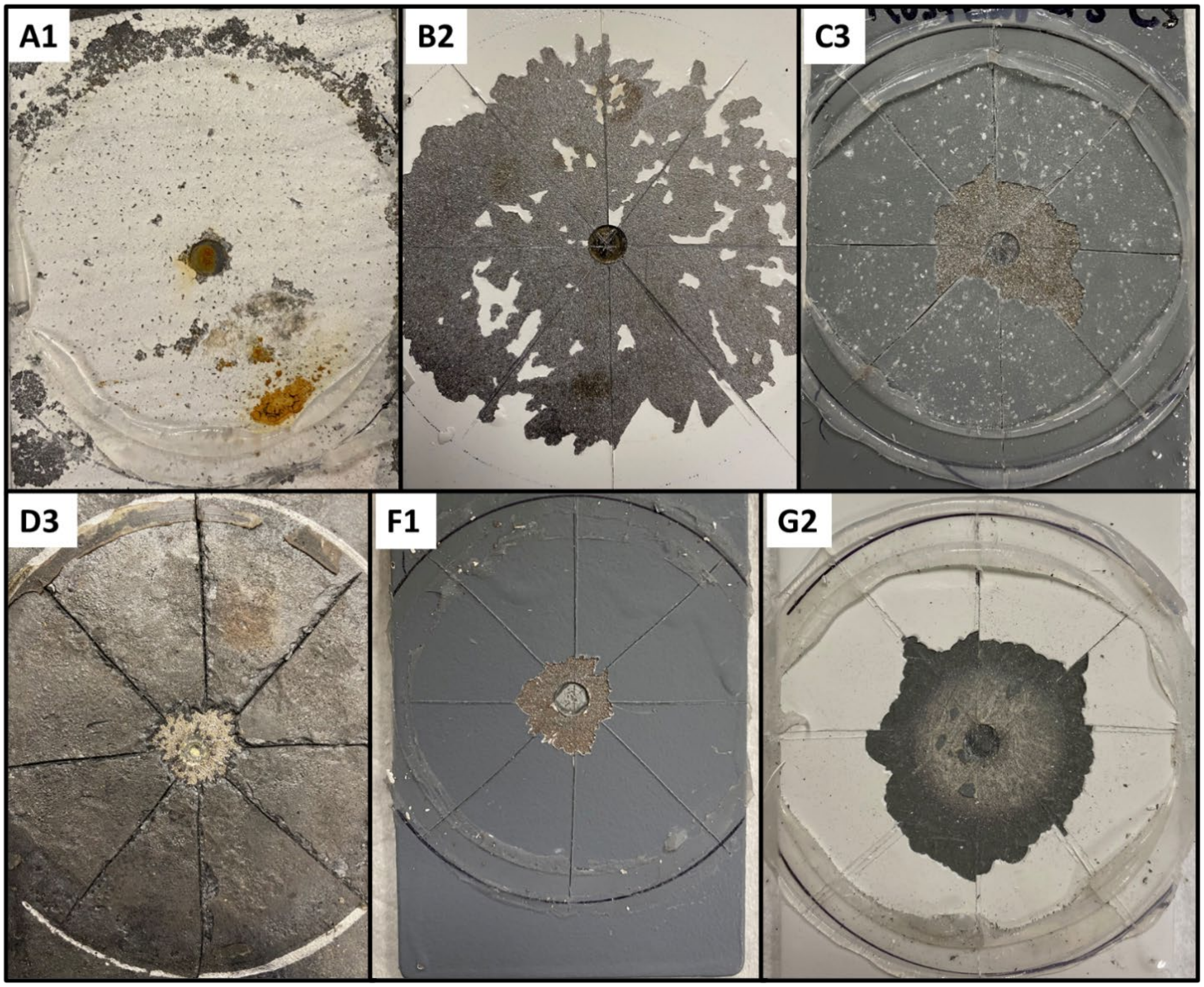

Figure 4: Cathodic disbondment specimens after disbondment evaluation. Top left to right: specimens A1, B2, and C3. Bottom left to right: specimens D3, F1, and G2. Note that disbondment for System G was only measured to the edge of the lightened ring visible around the holiday because the brittle coating broke away beyond the disbonded area.

Physical Testing

Taber Abrasion and Slurry Erosion

Taber abrasion was used to investigate the resistance of the coating surface to dry abrasion. Weight loss ranged from 75 to 93 mg for Systems B and C, respectively, to 820 mg for System A, as shown in Figure 5. Systems B and C provided the highest abrasion resistance, surpassing the two controls, Systems F and G, by a small amount. Systems A and D had very low resistance to abrasion.

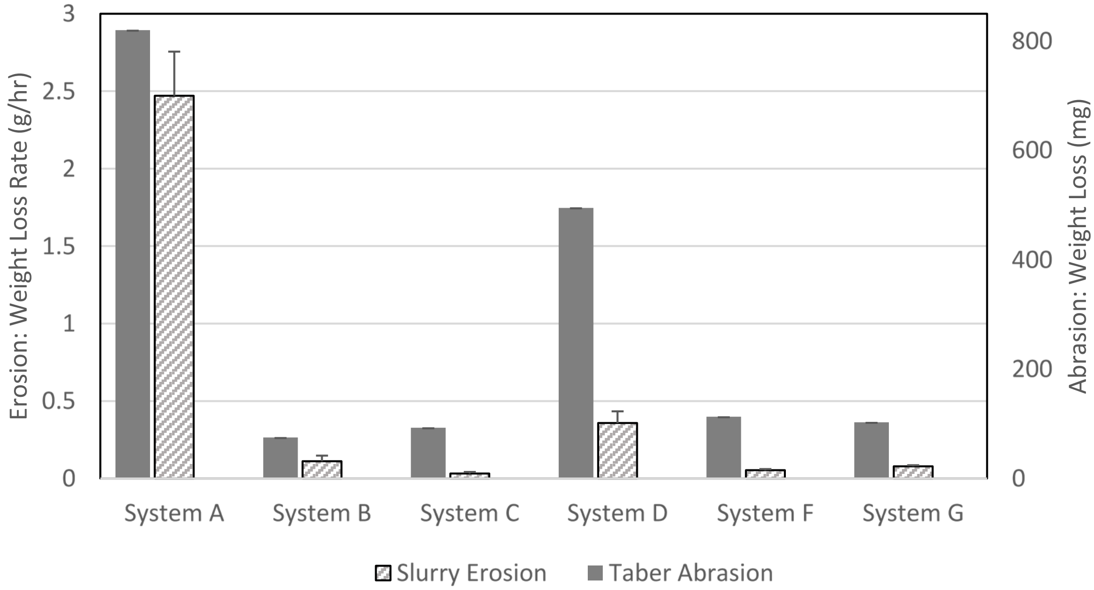

Figure 5: Taber abrasion (left bar) and slurry erosion (right bar) results.

Slurry erosion was used to investigate the resistance of the coating surface to erosive media entrained in agitated liquid. After 96 hours of exposure, a weight loss in grams per hour (g/hr) was calculated for each system. Figure 5 shows that weight loss ranged from 0.03 g/hr for System C to 2.47 g/hr for System A. System A had the highest weight loss from erosion, followed by System D. System C provided higher erosion resistance than all tested systems, including the two controls, Systems F and G.

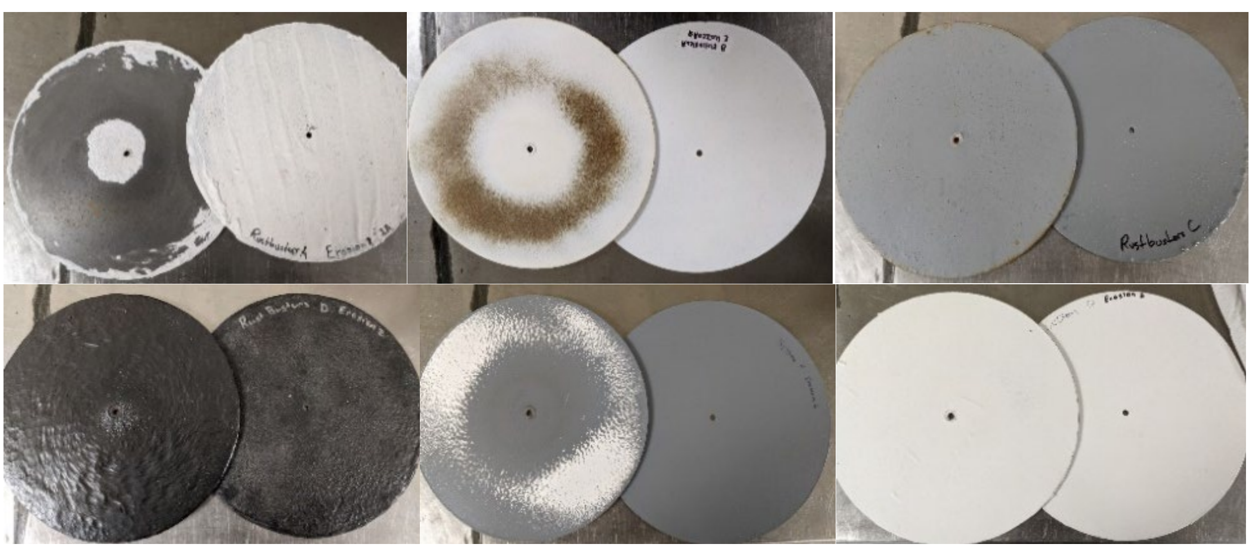

Figure 6: Slurry erosion photos before and after testing for Systems A, B, and C (top, left-to right) and Systems D, F, and G (bottom, left-to-right).

Visual representations of the slurry erosion performance before testing and after 96 hours of testing for each system are shown in Figure 6. The coating system wore through, revealed bare metal for

System A after just 24 hours and for System B after 96 hours. System F revealed the basecoat after 96 hours. The remaining coating systems retained their topcoat throughout the entirety of the test.

Impact Resistance

Impact testing uses a defined weight, dropped from various heights, to determine how much impact loading the coating can withstand before it fractures, and the substrate becomes visible. Thicker steel than specified by the standard was used to identify where the coating succumbed to impact damage rather than being damaged as a result of substrate deformation. Figure 7 shows the impact test results for Systems A, B, C, D, F and G. Systems B and F did not fail within the range of this test. System A had the lowest impact resistance, failing at a force at 1.6 N-m (14 in-lbs). System C, D, and G were very similar in performance at impact loads ranging from 4.1 to 5.0 N-m (36 to 44 in-lbs). Standard deviations were not obtained as only the testing used only one replicate.

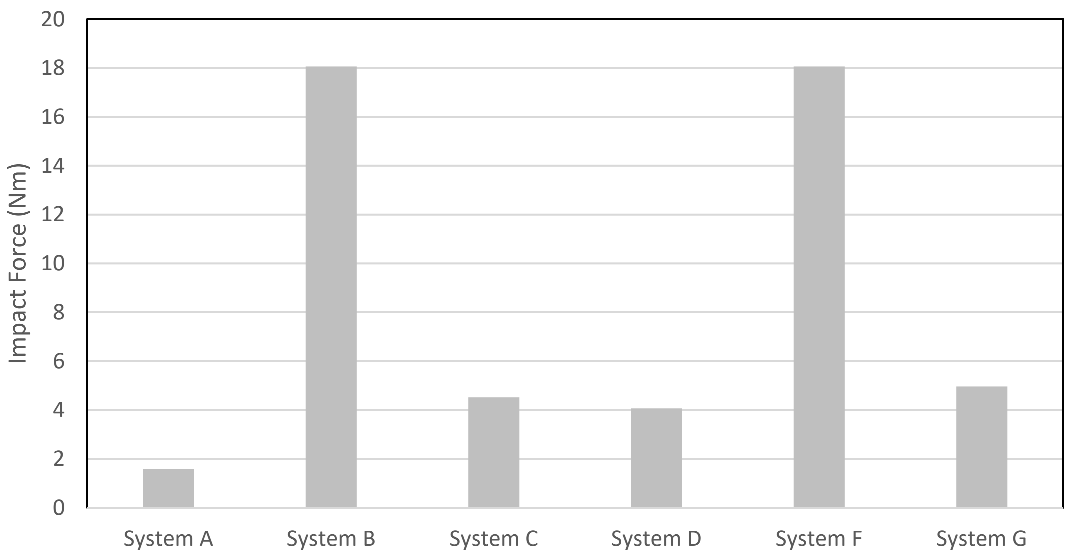

Figure 7: Drop weight impact test results.

Adhesion

Adhesion testing evaluated the bonding of each coating system to steel. Adhesion testing was performed on both dry samples with no immersion exposure and HAR immersion samples following 30 weeks of exposure (wet). Testing in these two conditions shows how the coatings adhesion performance changes resulting from immersion exposure. If the adhesion values dropped significantly between wet and dry, then that suggest its properties changed.

Figure 8 shows dry pull-off adhesion values and wet pull-off adhesion values as well as the failure mode as a fraction of total surface area for each coating system. System A failed in adhesion for the dry test at 7 MPa (102 psi). There were no wet adhesion samples for System A because it failed and was removed from immersion exposure testing.

Per ASTM D4541, Systems B, C, and F resulted in greater than 25% glue failure on all dollies in dry adhesion and should not be evaluated further, per the test method. For these systems, the actual dry adhesion strength is unknown, but it is equal to or greater than the results shown. By contrast, these systems had a 100% adhesion failure mode in the wet adhesion test. For Systems B and C, the adhesion strength decreased from the dry test to the wet test, indicating a reduction in this property in the HAR immersion exposure and lower adhesion values than the System F control. System F average total strength was unchanged in the wet adhesion test, and any change in the adhesion strength is unknown because there was a glue failure in the dry condition.

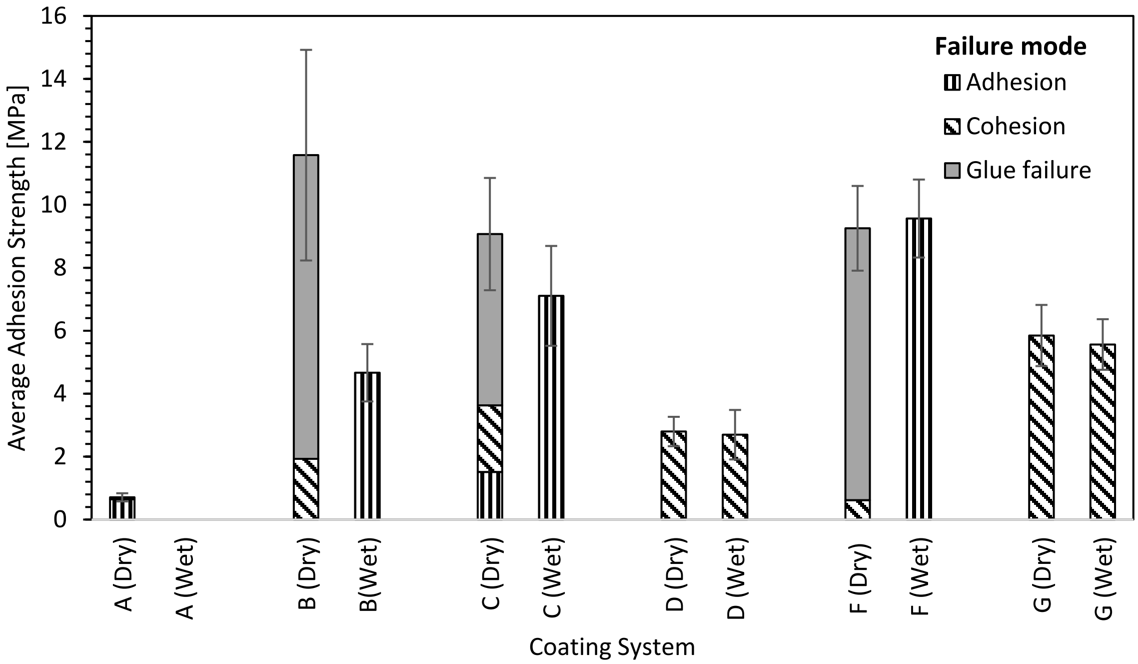

Figure 8: Dry and wet pull-off adhesion results with gradients representing the failure mode as a fraction of the total surface area.

Systems D and G both failed by cohesion in both dry and wet tests. The average pull-off strengths of these coatings were within a standard deviation, indicating no change in this property resulting from HAR immersion exposure. A cohesion failure substantially preserves the corrosion protection mechanism provided by a coating, while an adhesion failure is a total loss of protection.

Knife adhesion testing provided a qualitative assessment and ranking per ASTM D6677. The knife adhesion test evaluates how easily a coating can be physically removed from the metal substrate underneath following immersion exposure. Table 4 shows the ASTM rating, from 0-10, with 10 being excellent knife adhesion. Systems B and C performed similar to control System F, each with a rating of 4. System D had the highest ASTM rating of all the submitted solutions at 6 but rated slightly lower than the control System G.

Table 4. ASTM D6677 knife adhesion ratings, from 0-10.

System	DI ASTM Rating	HAR ASTM Rating
A*	0	0
B	4	4
C	4	4
D	6	6
F	4	4
G	8	8

**System A was removed from testing after 4 weeks due to coating degradation.*

Best Laboratory Performance Award

The Rust Busters prize competition acknowledges the best overall laboratory performer by combining testing results from all laboratory evaluations. Table 5 provides the corrosion and physical testing results shown as a total weighted score, in accordance with the prize competitions guidelines evaluation rubric. The maximum score possible was 30 points.

Table 5. Weighted rating results for corrosion and physical laboratory testing for Rust Busters A-D and control coating F and G.

Test Name	A	B	C	D	F	G	Max Points
Corrosion Testing: Immersion (HAR)	0	0	1.6	1.6	1.8	2	2
Corrosion Testing: Immersion (DI)	0	0	1.4	1.8	2	2	2
Corrosion Testing: Coating Barrier Properties (HAR)	0	1.5	0.9	1.2	2.7	2.7	3
Corrosion Testing: Coating Barrier Properties (DI)	0	1.8	0.9	1.2	2.7	2.7	3
Corrosion Testing: Cyclic Prohesion (PRO)	0	0	0	0.4	1	1.6	2
Corrosion Testing: Cyclic Prohesion + Immersion (BOR)	0	0.8	0	1.2	1	1.4	2
Physical Testing: Cathodic Disbondment	0	0	1.8	3	3	1.9	3
Physical Testing: Erosion Resistance	0	0.9	2.7	0.6	2.4	2.1	3
Physical Testing: Abrasion Resistance	0	1.6	1.2	0	0.8	0.8	2
Physical Testing: Impact resistance	0	3	1.2	0.9	3	1.2	3
Physical Testing: Pull-off adhesion (dry and wet)*	0.4	2	2.8	4	3.2	4	4
Physical Testing: Knife adhesion	0	0.4	0.4	0.6	0.4	0.8	1
Total Weighted Score	**0.4**	**12.9**	**14.9**	**16.5**	**24.0**	**22.2**	**30**

**Wet and dry adhesion results were 2 pts each and were combined in a comparative evaluation.*

System D accumulated the highest score and is deemed the Best Laboratory Performer with a total weighted score of 16.5 points. System C is the runner-up with a score of 14.9 points, followed by System B at 12.0 points. Systems A and E (not included in the paper) had the lowest point totals.

The experimental controls, Systems F and G, scored higher than all experimental systems tested, at 24.0 and 22.2 points, respectively.

Conclusion

The goal of the prize competition was to identify and develop new methods to protect hydraulic steel structures from corrosion. The paper reports the Phase 2 laboratory testing results for four of the five teams selected to provide prototypes. The evaluation of these coatings systems utilized water immersion exposure with electrochemical impedance spectroscopy evaluation, cyclic exposure testing, cathodic disbondment, Taber abrasion, slurry erosion, impact testing, and adhesion testing. The highest-ranking coating system from each evaluation are as follows:

- The corrosion resistance properties were poor for all systems and did not meet equivalent properties to the controls. System A, B, and C failed by early corrosion through coating, blistering, or cracking in several testing exposures. System D provided good undercutting resistance in DI and HAR water immersion.
- The results from EIS showed that all Phase 2 competitors had poor corrosion protection with low EIS magnitude and resistive properties. The controls outperformed all Phase 2 competitors.
- System D had the best cathodic disbondment resistance, and System C met the performance of the controls.
- Taber abrasion testing showed that abrasion resistance for Systems B and C exceeded controls F and G.
- Slurry erosion testing showed the highest erosion resistance for System C, which was similar to the controls. System B also had good erosion resistance, followed by System D.
- System B showed the highest impact resistance, equivalent to the control System F.
- Dry and wet testing adhesion results showed that System D and control G had no change in material properties after immersion testing, as measured by adhesion testing. Both failed a cohesive mechanism, and the corrosion protection at the interface between the coating and the substrate appeared to be undisturbed. System C and control F had the next highest performance in adhesion testing.
- Knife adhesion testing showed that System D and control G had the highest performance in this evaluation.

System D accumulated the highest point total and is acknowledged with the Rust Busters prize competition Best Laboratory Performer Award, followed by System C as the runner-up. System D is a robotic spray-applied coal tar enamel, and System C is a polysulfide coating with organometallo-phosphato polymer.

None of the experimental systems met the performance of the experimental controls, but several promising results were observed for novel materials and applications. The laboratory results demonstrated a unique set of corrosion performance properties and limitations for each coating system, offering a partial picture for their potential applications. Long term field testing will help show how the proposed solutions protect hydraulic steel structures under various environmental conditions, representing actual field service. Overall, the prize competition spurred innovation in corrosion protection options for hydraulic steel structures that can be further developed to advance the state of the art.

Acknowledgements

This prize competition was supported by the Research and Development Office of the Bureau of Reclamation. Special thanks are given to the U.S. Army Corps of Engineers Paint Technology Center, NASA Center for Excellence in Collaborative Innovation, and HeroX. Special thanks to interns Bo Raadam, Ellaena Rodriguez, Rachel Goddard, and Chloe Smith.

Disclaimer

Information in this paper may not be used for advertising or promotional purposes. The data and findings should not be construed as an endorsement of any product or firm by the Bureau of Reclamation or any other government agency.

References

[1] Bureau of Reclamation, "Bureau of Reclamation announces winners of the Long-Term Corrosion Protection of Existing Hydraulic Steel Structures Prize Competition," 27 June 2018. [Online]. Available: https://www.usbr.gov/newsroom/newsroomold/newsrelease/detail.cfm?RecordID=62570. [Accessed 8 July 2021].

[2] HeroX, ""Rust Busters Challenge", Challenge Guidelines," 2021. [Online]. Available: https://www.herox.com/RustBusters/guidelines. [Accessed 6 July 2021].

[3] "SSPC-SP 1, Solvent Cleaning," 2016.

[4] "SSPC-SP5(WAB)/NAC WAB-1, White Metal Wet Blast Cleaning," 2015.

[5] NACE SP0169, "Control of External Corrosion on Underground or Submerged Metallic Piping Systems," in NACE, Houston, TX, 2013.

[6] ASTM International, "ASTM D870-15 Standard Practice for Testing Water Resistance of Coatings Using Water Immersion," Conshohocken, 2020.

[7] ASTM International, "D1654-08 Standard Test Method for Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments," West Conshohocken, 2016.

[8] ASTM International, "D5894-16 Standard Practice for Cyclic Salt Fog/UV Exposure of Painted Metal, (Alternating Exposures in a Fog/Dry Cabinent and a UV/Condensation Cabinent)," Conshohoken, 2016.

[9] NACE TM0115, "Cathodic Disbondment Test for Coated Steel Structures Under Cathodic Protection," in *NACE*, Houston, TX, 2015.

[10] ASTM International, "D4060-19 Standard Test Method for Abrasian Resistance of Organic Coatings by the Taber Abraser," West Conshohocken, 2019.

[11] ASTM International, "D2794-93 Standard Test Method for Resistance of Organic Coatings to the Effects of Rapid Deformation (Impact)," West Conshohocken, 2019.

[12] ASTM International, "D4541-17 Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers," West Conshohocken, 2017.

[13] ASTM International, "ASTM D6677-18 Standard Test Method for Evaluating Adhesion by Knife," West Conshohocken, 2018.

[14] ASTM International, "D4587-11 Standard Practice for Fluorescent UV-Condensation Exposures of Paint and Related Coatings," Conshohoken, 2019.

[15] ASTM International, "G85-19 Annex A5 Dilute ElectrolyteCyclic FOG/DRY Test," Conshohocken, 2019.

[16] NACE SP0188, "Discontinuity (Holiday) Testing of New Protective Coatings on Conductive Substrates," in *NACE*, Houston, TX, 2006.

[17] R. C. Bacon, J. Smith and F. Rugg, *Industrial and Engineering Chemistry,* vol. 40, p. 161, 1948.