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Selecting Primers for Cavitation Resistant Coating Systems

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Cover Image – A coated turbine runner for field validation of proprietary coating formulations (Bureau of Reclamation).

Selecting Primers for Cavitation Resistant Coating Systems

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

Final Report ST-2026-24005-02, 8540-2026-16

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Acronyms and Abbreviations

AWWA	American Water Works Association
BOR	modified Prohesion adding a water immersion cycle, developed by Bureau of Reclamation
cm ²	centimeters squared
DI	deionized water immersion
DFT	dry film thickness
ECM	equivalent circuit modeling
EIS	electrochemical impedance spectroscopy
EPA	Environmental Protection Agency
FOG	salt fog cabinet test
ft/s	feet per second
HAR	dilute Harrison's solution water immersion
hr	hour
hrs	hours
Hz	Hertz
in.	inch
in-lbs	inch pounds
MC	moisture cure
mg	milligrams
mm	millimeters
mm ³	millimeters cubed
m/s	meters per second
mV	millivolts
N/A	not applicable
PE 1	Polyurethane Elastomer 1
PE 2	Polyurethane Elastomer 2
pli	pounds per linear inch
PRO	Prohesion cyclic testing
psi	pounds per square inch
QUV	condensation and UV cycles
Reclamation	Bureau of Reclamation
SCE	saturated calomel electrode
S&T	Science and Technology Program
TVA	Tennessee Valley Authority
US	United States
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation

UV	ultraviolet
VOC	volatile organic compound

Symbols

>	greater than
/	per
&	and
%	percent

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Executive Summary

Hydropower infrastructure such as turbine runners, valves, and outlet pipes are frequently exposed to high-velocity water flows that cause cavitation damage. Traditional repair methods, including stainless-steel weld overlays, are costly, time-consuming, and often require frequent maintenance. Existing commercial coatings fail quickly under mild to moderate cavitation conditions, leading to increased downtime, reduced power generation, and higher operational costs. There is a critical need for durable, field-applicable coatings that can extend the service life of these components and reduce maintenance frequency.

The current S&T project consisted of the following three tasks. Final report ST 2026-24005-01 covers Tasks 1 and 2, and this Final report ST 2026-24005-02 covers Task 3.

1. Continuation of monitoring prior field trials of the commercially available cavitation resistant coatings on Grand Coulee G21 turbine runner.
2. Field trials of Bureau of Reclamation developed cavitation resistant coatings.
3. Laboratory corrosion protection assessment of Bureau of Reclamation developed cavitation resistant coatings.

This Final report ST-2026-24005-02 investigated compatibility between the Reclamation developed cavitation resistant coating with various commercial primers or complete coating systems to provide cavitation, erosion, and corrosion protection in high-velocity water environments. The goal of the study is to identify multiple primers or coating systems. Further, this investigation aides Reclamation in identifying potential coating manufacturers to license the technology.

Two sequential studies were performed. The baseline laboratory study investigated the original Reclamation formulation T0 and compared it to the best commercially available cavitation resistant coating systems from S&T project 20024. The baseline study showed Epoxy 1 + T0 to perform similarly to the commercial products. Peel adhesion correlated to the cavitation results; therefore, peel adhesion was used for pre-screening primers for the subsequent study. Peel adhesion using the optimized T4.5 elastomer identified four primers (Epoxy 1, Epoxy 10, Polysiloxane 1, and Vinyl System 5EZ) to advance to the corrosion protection study. However, Epoxy 10 was not identified in time to be included. Each of the three primers evaluated met the testing requirements for corrosion protection in water immersion service, cathodic disbondment resistance, erosion resistance, and cavitation resistance.

This project demonstrated multiple primers for use in a complete system. While Reclamation currently specifies Epoxy 1, Polysiloxane 1, and Vinyl System 5EZ for long-term corrosion protection in water immersion service, adding the T4.5 elastomer as a topcoat could solve erosion and cavitation service conditions where these primers are damaged.

Implementing the developed cavitation resistant coating into field use requires additional understanding of the cavitation intensity and unit capacity limits for these coatings. The ongoing

field trials at Nathaniel Washington Powerplant on the Unit G21 turbine runner at Grand Coulee Dam and Estes Powerplant Unit 2 turbine runner will continue to provide valuable long-term testing data. Current findings show the coatings are effective up to an unknown threshold of cavitation intensity.

This laboratory study confirmed that future field trials should use Epoxy 1, Polysiloxane 1, and Vinyl System 5EZ primers with T4.5 elastomer. Additional field trials should be installed selecting facilities for cavitation intensity and unit capacity. In addition, full-scale runner applications in erosion environments should also be investigated.

1.0 Introduction

Hydropower infrastructure components—including turbine runners, valves, and pipes—are routinely subjected to high-velocity water flows, greater than 100 feet per second (ft/s) (30.5 meters per second (m/s)), that result in cavitation damage. Conventional repair methods, such as stainless-steel weld overlays, are expensive, labor-intensive, and often necessitate recurrent maintenance. Currently available commercial coatings tend to fail within one maintenance cycle, 2-3 years, even under mild to moderate cavitation. Consequently, there is a significant demand for robust, field-deployable coatings capable of extending component lifespans and minimizing maintenance intervals.

Science and Technology Program (S&T) project 20024 “Laboratory Evaluation of Field Repairable Materials and Techniques for Cavitation Damage: Phase II,” evaluated two commercially available polyurethane elastomers (PE1, PE2) demonstrating cavitation resistance approximately twentyfold longer in the test procedure than previously used coatings [1]. Field trials began in 2023 at Nathaniel Washington Powerplant on the Unit G21 turbine runner at Grand Coulee Dam and Flatiron Powerplant on the Unit 2 butterfly valve [2]. Following six weeks of operational use, the PE 1 coating at Grand Coulee exhibited some damage within the most severe cavitation zone, whereas PE 2 had large disbondment areas [2]. Flatiron Unit 2 Butterfly has not been inspected since installation.

Insights from project 20024 provided ideas for advancements in technology, prompting the initiation of S&T project 23009 “Investigating Rubberized Coating Formulations,” focused on developing a cavitation resistant coating [3]. Researchers engineered an experimental thermoplastic elastomer formulation (T0) alongside several rubberized formulations (T1.5, T3, T4.5, and T6) [3]. The Estes field trial validated the suitability of these formulations in real-world cavitation conditions [4].

The current study consisted of the following three tasks. Final report ST 2026-24005-01 covers Tasks 1 and 2 [2], and this Final report ST 2026-24005-02 covers Task 3:

1. Continuation of monitoring prior field trials of the commercially available cavitation resistant coatings on Grand Coulee G21 turbine runner, which were installed under S&T project 20024.
2. Field trials of Bureau of Reclamation developed cavitation resistant coatings
3. Laboratory corrosion protection assessment of Bureau of Reclamation developed cavitation resistant coatings.

This Final report ST-2026-24005-02 investigated compatibility between the Reclamation developed cavitation resistant coating with various commercial primers or complete coating systems, e.g. Vinyl System 5EZ, to provide long-term cavitation (or erosion) and corrosion protection in high-velocity water environments. The goal of the study is to identify multiple primers or coating systems to allow more competition and product availability. Further, this investigation aides Reclamation in identifying potential coating manufacturers to license the

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technology. Ultimately, identification of effective and durable primers allows all Government Departments the versatility to use these coating systems for erosion, cavitation, and corrosive environments.

This research is partnered with the United States Army Corps of Engineers (USACE) and the US Navy. The use of Military Specification epoxy primers with the cavitation resistant coatings would allow other Government agencies to easily incorporate the Reclamation developed cavitation resistant coating into their specifications. Also, evaluating USACE Vinyl Systems 4 and 5EZ with the cavitation resistant coating was desired by USACE and to add as a topcoat in severe conditions.

Two sequential studies were performed to identify primer systems for the cavitation resistant polyurethane elastomer topcoat. The baseline laboratory study investigated the original Reclamation formulation T0 and compared it to the best commercially available cavitation resistant coating systems from S&T project 20024 [1]. A subsequent study evaluated the optimized formulation T4.5 with a broader set of candidate primers. The primers were screened using ASTM D429 90-degree peel adhesion of elastomers to a rigid substrate in both wet and dry conditions [5]. Corrosion protection properties were evaluated for systems demonstrating good wet and dry adhesion. Some primers with poor wet adhesion were selected to illustrate adhesion's effect on corrosion resistance properties and cavitation resistance.

The expected outcome of this project was to identify several primers compatible with the Reclamation developed cavitation resistant coating, as determined by good wet and dry adhesion, corrosion protection, and cavitation and erosion resistance. This project was conducted in collaboration with key stakeholders in the hydroelectric industry, with the goal of providing practical solutions to critical challenges in severe cavitation and erosion service conditions.

2.0 Materials

The coating systems used for the T0 elastomer study in this report are coded and listed in Table 1 comparing commercially available cavitation resistant coatings. Product coating description, approved standards, and notes are listed. This first study compared commercially available cavitation resistant coatings to Reclamation T0 elastomer formulation over two primer systems, both commercial epoxies. Epoxy 1 was a traditional corrosion resistant primer, and Epoxy 2 primer was a surface tolerant epoxy that met American Water Works Association (AWWA) D102.

Table 1.—T0 elastomer coating system report codes

Code	Primer Description	Topcoat Description	Standards/ Notes
PE 1	100% solids abrasion resistant epoxy primer	Abrasion and cavitation resistant elastomeric polyurethane	Commercial product
PE 2	Corrosion resistant epoxy primer	Abrasion resistant urethane rubber	Commercial product, discontinued in 2024
Epoxy 1 + T0	Corrosion resistant epoxy primer	Abrasion and cavitation resistant elastomeric polyurethane	Primer - SSPC Paint 16, MPI #101, Mil-PRF-23236
Epoxy 2 + T0	Surface tolerant corrosion resistant epoxy primer	Abrasion and cavitation resistant elastomeric polyurethane	Primer - AWWA D102

Table 2 provides coating system product codes used in identifying compatible primers with T4.5 elastomer. Primers were selected for chemistry type and primarily for Government purposes, including Military Specification approved coatings that meet Mil-PRF-23236 epoxy, Mil-PRF-24647 epoxy, or Mil-PRF-24635 polysiloxane. Additionally, the study included USACE Vinyl System 4 (four-double spray coats of V-766E) and Vinyl System 5EZ (one-double spray coat of VZ-108d plus three double spray coats of V766E).

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Table 2.—Coating system report codes for primer selection for T4.5 elastomer

Code	Primer Description	Topcoat Description	Standards/ Notes
System 4	Vinyl V-766E	Vinyl V-766E	USACE Vinyl System 4
System 4 + T4.5	Vinyl V-766E	Optimized cavitation resistant elastomeric polyurethane	USACE Vinyl System 4
System 5EZ	Vinyl VZ-108d	Vinyl V-766E	USACE Vinyl System 5EZ
System 5EZ	Vinyl VZ-108d /V-766E	Optimized cavitation resistant elastomeric polyurethane	USACE Vinyl System 5EZ
Epoxy 1	Corrosion resistant epoxy primer	N/A	Primer - SSPC Paint 16, MPI #101, Mil-PRF-23236
Epoxy 1 + T4.5	Corrosion resistant epoxy primer	Optimized cavitation resistant elastomeric polyurethane	Primer - SSPC Paint 16, MPI #101, Mil-PRF-23236
Epoxy 3	Phenalkamine corrosion resistant epoxy primer	N/A	Primer - SSPC-Paint 16, Mil-PRF-23236, Mil-PRF-24647
Epoxy 3 + T4.5	Phenalkamine corrosion resistant epoxy primer	Optimized cavitation resistant elastomeric polyurethane	Primer - SSPC-Paint 16, Mil-PRF-23236, Mil-PRF-24647
Epoxy 4	Polyamine corrosion resistant epoxy primer	N/A	Primer - SSPC-Paint 16, Mil-PRF-23236, Mil-PRF-24647
Epoxy 4 + T4.5	Polyamine corrosion resistant epoxy primer	Optimized cavitation resistant elastomeric polyurethane	Primer - SSPC-Paint 16, Mil-PRF-23236, Mil-PRF-24647
Epoxy 5 + T4.5	Phenalkamine corrosion resistant epoxy primer	Optimized cavitation resistant elastomeric polyurethane	Primer - Mil-PRF-23236, Mil-PRF-24647
Epoxy 6 + T4.5	Phenalkamine corrosion resistant epoxy primer	Optimized cavitation resistant elastomeric polyurethane	Primer - Mil-PRF-23236, Mil-PRF-24647
Epoxy 7 + T4.5	Phenalkamine corrosion resistant epoxy primer	Optimized cavitation resistant elastomeric polyurethane	Primer - Mil-PRF-23236, Mil-PRF-24647
Epoxy 8 + T4.5	Phenalkamine corrosion resistant epoxy primer	Optimized cavitation resistant elastomeric polyurethane	Primer - Mil-PRF-23236, Mil-PRF-24647
Epoxy 9 + T4.5	Phenalkamine corrosion resistant epoxy primer	Optimized cavitation resistant elastomeric polyurethane	None
Epoxy 10 + T4.5	Phenalkamine corrosion resistant epoxy primer	Optimized cavitation resistant elastomeric polyurethane	None
MC Urethane 1 + T4.5	Surface tolerant moisture cured urethane	Optimized cavitation resistant elastomeric polyurethane	None
Polysiloxane 1	Cycloaliphatic epoxy - polysiloxane	N/A	Primer - MIL-PRF-24635
Polysiloxane 1 + T4.5	Cycloaliphatic epoxy - polysiloxane	Optimized cavitation resistant elastomeric polyurethane	Primer - MIL-PRF-24635
Polysiloxane 2 + T4.5	Cycloaliphatic epoxy - polysiloxane	Optimized cavitation resistant elastomeric polyurethane	Primer - MIL-PRF-24635
Polysiloxane 3 + T4.5	Cycloaliphatic epoxy - polysiloxane	Optimized cavitation resistant elastomeric polyurethane	Primer - MIL-PRF-24635

The primers selected in Table 2 included several unique cases. First, surface tolerant moisture-cure (MC) urethane primers were used to see if minimal surface preparation could be performed instead of abrasive blast cleaning. Second, a 100-percent (%) solids epoxy with similar chemistry to the Mil-PRF-23236 epoxies was included.

The Reclamation T0 and T4.5 elastomers are proprietary polyurethanes. These systems utilize a proprietary adhesive between the primer and Reclamation elastomer.

3.0 Testing Protocols

Reclamation's standard testing protocol focusing on corrosion, adhesion, erosion, and cavitation properties are listed below, and the rating criteria can be found in Appendix A. The rating criteria allow for comparison to Reclamation's previously tested coatings.

- HAR - Immersion in a dilute Harrison's solution (HAR), 0.5 g sodium chloride and 3.5 g ammonium sulfate per liter of deionized (DI) water (ASTM D870 Modified) [6]
- DI - Immersion in DI water (ASTM D870) [6]
- PRO - Prohesion cyclic testing (weekly rotation, QUV-FOG) (ASTM D5894) [7]
- BOR - Modified Prohesion cyclic test (weekly rotation, QUV-FOG-HAR-FOG)
- FOG - Prohesion testing in a salt fog test cabinet (ASTM G85 Annex A5) [8]
- QUV - Condensation and ultraviolet (UV) cyclic test (ASTM D4587 cycle 2) [9]
- Electrochemical impedance spectroscopy (EIS) (ISO 16773-2) [10]
- Wet and dry pull-off adhesion testing (ASTM D4541) [11]
- Peel adhesion testing (ASTM D429) [5]
- Knife adhesion testing (ASTM D6677) [12]
- Direct impact testing (ASTM D2794) [13]
- Cathodic disbondment (ASTM G8) [14]
- Erosion resistance (USBR-5071-2015) (Appendix B)
- Cavitation resistance (USBR Test Procedure) (Appendix C)

The first seven tests from the list exposed test panels for approximately 30 weeks (5040 hours (hrs)) in accordance with industrial standard practices. Panel evaluation, for the coatings that endured the entire testing protocol, proceeded according to ASTM D1654, *Standard Test Method for Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments (rust creep)*, and ASTM D714, *Standard Test Method for Evaluating Degree of Blistering of Paints* [15] [16]. Two panels for HAR, DI immersion, BOR, and PRO, and one for FOG, and QUV tests were scribed down the center on one panel face with a Dremel[®] tool. The scribes were approximately 1 millimeter in width and 3 inches in length to expose the steel substrate. This scribe allows researchers to determine the degree of undercutting resistance the systems provide. Further details for each test are provided in the sections below.

3.1. Water Immersion

HAR and DI corrosion testing was performed on coated 3 in. x 6 in. x 1/8 in. steel test panels in designated tanks. These immersion panels were suspended from hooks through pre-cut holes. Each tank was sufficient to fully submerge the panels. To ensure homogeneity, the HAR solutions were mixed before addition to the tank. Each tank was connected to a filtration system that circulated the solutions, with the tanks cleaned, and solutions replaced once a year. Samples were evaluated after 5040 hrs of exposure.

3.2. Cyclic Testing

PRO, BOR, FOG, and QUV cyclic testing was performed on coated 3 in. x 6 in. x 1/8 in. steel test panels in designated testing apparatuses. The testing procedures followed ASTM protocols listed above with the exception of BOR. The BOR test is a modified Prohesion test, used by Reclamation, intended to simulate the effects of a fluctuating immersion environment/splash zone. Panels in cyclic testing were rotated every week, and samples were evaluated after 5040 hrs of exposure.

3.3. Electrochemical Impedance Spectroscopy Testing

Two unscribed panels of HAR and DI, and one unscribed panel of PRO and BOR were evaluated using EIS following ISO 16773-2 procedures, performed with a Gamry Instruments Reference 620 potentiostat [10]. Measurements used 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; a saturated calomel electrode (SCE), platinum mesh electrode, and the steel substrate were connected to the instrument as the reference, counter, and working electrode, respectively. The EIS testing surface area, as defined by the test cell's O-ring, is 23 centimeters squared (cm^2). Raw data was normalized for surface area to present impedance magnitude in ohm-cm^2 . EIS was performed periodically throughout the exposure conditions over a 30-week period. If coatings performed well during the 30-week evaluation, long-term testing in water immersion service commenced to allow for monitoring of the barrier properties over time.

3.4. Adhesion

3.4.1. Pull Off Adhesion

Six replicates for pull off adhesion utilized a loading fixture (20-millimeter (mm) dolly), which is attached to a coating surface with an adhesive. A pull off adhesion tester (DeFelsko Positest AT) was used to gradually apply an increasing load on the dolly until it is “pulled” off. The force that was required to pull off the dolly is the yield strength, measured in pounds per square inch (psi). Dry adhesion testing was performed on test panels that were not exposed to immersion, and wet adhesion on test panels exposed to at least 6 months of immersion (wet adhesion). For the wet adhesion tests, the panels were removed from HAR, wiped dry, surface abraded with 120 grit sandpaper, and dollies were glued down. The panels were placed in Reclamation's 100% humidity room for 24 hrs, then removed and tested within one hour (hr). Adhesion pull-off tests did not exclude greater than 20% glue failure in accordance with the standard due to the significant amount of glue failures in the data set due to gluing dollies to an elastomer.

3.4.2. Peel Adhesion

Peel adhesion requires a 2 in. flap section of elastomer to attach grips with the remaining elastomer coat adhered to primer-coated steel panel. Two one-inch strips were cut longitudinally in the center of the panels to follow the ASTM testing procedure. The samples were clamped in the testing apparatus, and the elastomer flap was inserted into the grips. Force was applied to the elastomer, until it broke or disbonded from the primer or steel substrate. Dry and wet adhesion (1 month in water immersion) was performed. A total of six samples were collected for each coating system and adhesion type, measuring the force in pounds per linear inch (pli).

3.4.3. Knife adhesion

Knife adhesion specified by ASTM D6677 is a qualitative test to evaluate if coatings adhere to substrates [12]. Failure to the substrate or between coats is recorded and the rating is the size of paint chips that were removed. This test was only performed on wet samples after 6 months of water immersion service.

3.5. Rapid Deformation Direct Impact

Impact testing was done following the ASTM D2794 test method [13]. This test method exposes the coating systems to the effects of rapid deformation (impact) utilizing a manually operated impact testing machine that drops a pre-determined weight onto the coating surface. The test value is reported in inch-pounds (in-lbs) and represents the threshold of impact that a coating system can endure without cracking or developing a holiday. Values for the Reclamation cavitation resistant coating system were determined when the impact penetrated the elastomer exposing the primer, not damage to the substrate.

3.6. Cathodic Disbondment

Cathodic disbondment assesses coating damage from prolonged overpotential from a cathodic protection system. This procedure produces hydroxide (strong base) at the defect and sometimes disrupts adhesion mechanisms, causing coating disbondment. While cathodic protection may not be effective in high-velocity water service conditions, end-users may use these coating systems in different conditions where cathodic protection is used, and it is important to understand the limitations. Cathodic disbondment followed ASTM G8 method A test procedure [14].

3.7. Slurry Erosion

The slurry erosion test is a Reclamation standard following the USBR-5071-2015 testing procedure, described in Appendix B [17]. Coated 11-in. diameter, 1/8-in. thick steel discs were used. The test duration was 96 hrs per sample. There were two samples per coating system. The average weight loss in milligram (mg) was compared between samples and a control disc that

remained submerged in the DI tank. The weight loss was normalized by dividing by the density of the material and surface area to get an average thickness loss in microns.

3.8. Cavitation

The cavitation test apparatus was developed under S&T project 8452 “Evaluation of Field Repairable Materials and Techniques for Cavitation Damage,” described in Appendix C [18]. Cavitation testing was performed on two coated 3 in. x 6 in. x 1/8 in. steel test panels, with four 1/4-in. holes drilled in the corners. The panels were then fastened to a steel block 4 in. x 6 in. x 5/8 in. and placed into the cavitation tank. Panels were monitored frequently during business hours, but also were exposed overnight, for up to 16 hrs without observation. The samples were exposed to cavitation for up to 250 hrs or until coating failure.

4.0 Baseline Corrosion Resistance of T0 Elastomer

The experimental design is to perform baseline corrosion resistance testing of the T0 formulation with two different primers and compare to the commercially available cavitation resistant coatings. This study will aid in determining flaws in the research design to improve the evaluation of the optimized T4.5 formulation.

4.1. Surface Preparation and Coating Application

Samples were prepared using A36 carbon steel. Each coating system had a set of twenty-four 3 in x 6 in. x 1/8 in. steel coupons, two 11-in. diameter x 1/8-in. thick round disks, and one 3-in. diameter x 1-foot section of pipe. Surface preparation for samples consisted of removing oil and contaminants by detergent cleaning following SSPC-SP1 [19]. Next, they were abrasive blast cleaned to SSPC-SP 5/NACE 1 with an angular profile of 3.0 mils [20].

Reclamation applied commercially available coatings in accordance with coating manufacturers’ instructions. Coating systems were cured for a minimum of one week prior to testing.

4.1.1. PE 1 Cavitation Resistant Coating System

For commercial coating system PE1, the ceramic filled epoxy primer was applied using a brush and troweled smooth following manufacturer’s instructions at 70-degrees Fahrenheit. The dry film thickness (DFT) was not measured due to application method being non-uniform. The ceramic filled epoxy primer was cured for 12-24 hrs, then the panels were brush-off blast cleaned to SSPC-SP7 [21] to roughen the coating surface as instructed by manufacturer’s product data sheet. After the surface preparation, the conditioner (adhesive) was applied using a brush as thin

as possible, excess conditioner was removed by dry brushing. The conditioner was cured for 2 hrs. PE 1 was applied to approximately 30-40 mils DFT.

4.1.2. PE 2 Cavitation Resistant Coating System

Commercial coating system PE2 was applied to commercial Epoxy 1. Three coats of corrosion resistant Epoxy 1 were sprayed at 4-6 mils per coat for a total of 12-18 mils DFT. After the final coat was cured for 12-24 hrs, the Reclamation adhesive was brushed to Epoxy 1 without additional surface preparation. The adhesive was allowed to cure for 2 hrs. PE 2 was brush applied at 30-40 mils DFT.

4.1.3. Epoxy 1 – Reclamation T0 Cavitation Resistant Coating Systems (Epoxy 1 + T0)

Three coats of corrosion resistant Epoxy 1 were sprayed at 4-6 mils per coat for a total of 12-18 mils DFT. After the final coat was cured for 12-24 hrs, the Reclamation adhesive was brushed onto Epoxy 1 without additional surface preparation. The adhesive was cured for 2 hrs. Reclamation T0 elastomer was roller applied at 30-40 mils DFT.

4.1.4. Epoxy 2 - Reclamation T0 Cavitation Resistant Coating Systems (Epoxy 2 + T0)

Three coats of Epoxy 2 were sprayed at 4-6 mils per coat for a total of 12-18 mils DFT. After the final coat was cured for 12-24 hrs, the Reclamation adhesive was brushed onto to Epoxy 2 without additional surface preparation and cured for 2 hrs. Reclamation T0 elastomer was applied at 15-20 mils DFT, and a second coat was applied 2 hrs after the first T0 coat was roller applied to reach the desired total of 30-40 mils of elastomer.

4.2. T0 Elastomer Results

4.2.1. Water immersion

Figure 1 shows the undercutting resistance of the coating systems evaluated with the scale adjusted for direct comparison to Section 4.2.2. Cyclic Exposure. Epoxy 1 + T0, and Epoxy 2 + T0 had no undercutting in DI and HAR. PE 1, and PE 2, had a small amount of undercutting in HAR, but no undercutting in DI immersion. Undercutting was not uniform and often not measurable, resulting in large standard deviations where it did occur. No blistering or cracking was observed on any of the coating systems test panels. Barrier properties were evaluated on two identical panels using a three-electrode EIS setup.

Selecting Primers for Cavitation Resistant Coating Systems

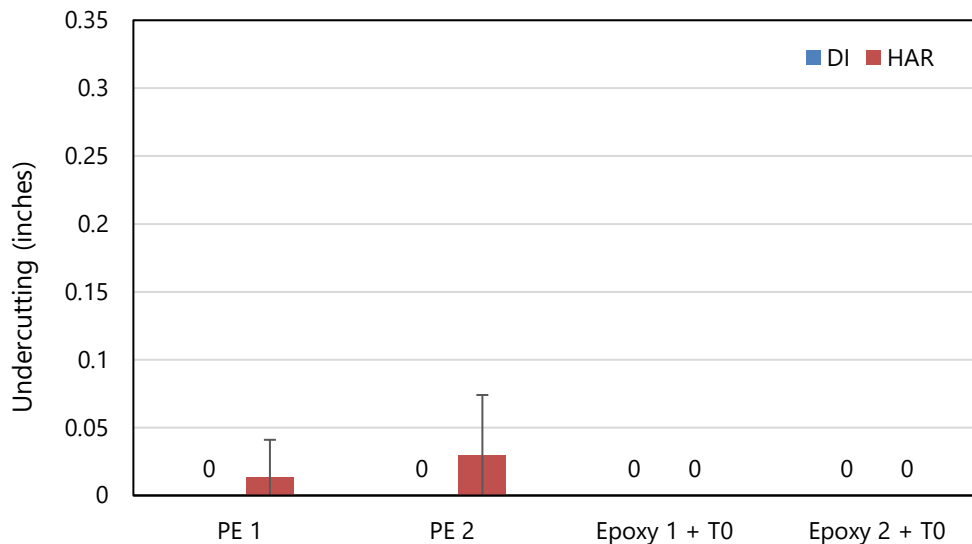


Figure 1. Baseline corrosion undercutting in DI and HAR water immersion after 5040 hrs of exposure, with a "0" provided where no undercutting occurred; scaled to a maximum of 0.35 in. for direct comparison to cyclic exposure results.

4.2.2. Cyclic Exposure

The undercutting corrosion was greater for the cyclic weathering compared to water immersion, due to more cycles of wetting and drying, which induces stress to the coating. Wetting causes the coatings to swell and expand whereas drying causes the coating to shrink and contract. The repeated wetting and drying stresses increase corrosion creep under the coating along the steel interface.

Figure 2 shows the coatings have similar undercutting in each cyclic test, with mean values around 0.2 ± 0.05 in. This is a good undercutting rating according to the test protocol. Note that PE1 and PE2 were not tested in FOG exposure due to several panels becoming unusable during the topcoat's brush-off blast surface preparation. Undercutting was again not uniform, resulting in large standard deviations and occasional different results between the two panels. PE 1, PE 2, Epoxy 1 + T0, and Epoxy 2 + T0 had yellowed, changed color, and chalked in PRO and BOR testing due to the UV exposure.

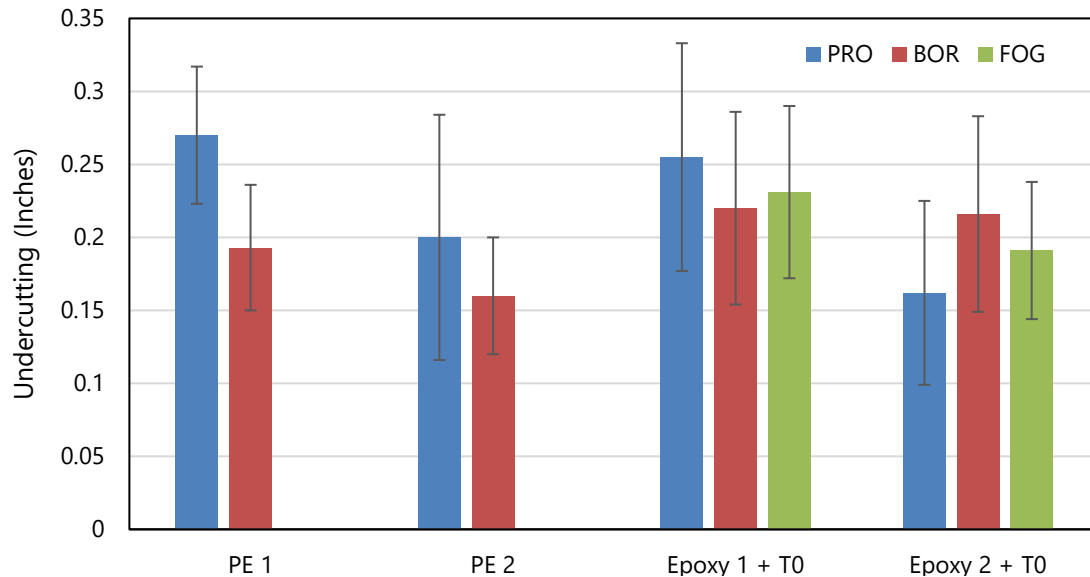


Figure 2. Undercutting corrosion in different cyclic weathering after 5040 hrs for initial study; PE1 and PE2 not evaluated in FOG exposure.

4.2.3. Electrochemical Impedance Spectroscopy

EIS was not collected for PE 1 and PE 2 due to the coating surface being too rough to attach the electrochemical cells to the surface. The roughness was due to the products being paste-grade materials.

Epoxy 1 + T0 had high impedance magnitude but also showed resistive behavior in the phase angle plot, as shown in Figure 3. It is hypothesized that, when modeled, the primer has higher resistance, and the elastomeric topcoat has lower resistance (porous), which produces a plot that shows a resistive peak (minimum) at distinct frequencies for these in-series components of the coating system. The full primer study in Section 5 includes data for the primer without the topcoat to help confirm the source of various features in the curve. Equivalent circuit modelling (ECM) should be performed on these coating systems but was outside the scope of this project. ECM can provide values for resistive and capacitive (often modeled as a constant phase element) features of the coating system and the coating/steel interface separately.

HAR, PRO, and BOR exposures produce significant changes for Epoxy 1 + T0. The first month shows an increase in low frequency impedance magnitude and more negative phase angles, indicating more capacitive behavior. After the first month the impedance magnitude at 0.01 Hz decreases but remains above 10^{10} ohms-cm² for the duration of the test. The phase angle plot shows a second time constant, i.e., inflection point in the curve, by the end of testing, which usually is an indicator of active corrosion at the substrate. DI exposure had similar curve features but minimal change during exposure.

Selecting Primers for Cavitation Resistant Coating Systems

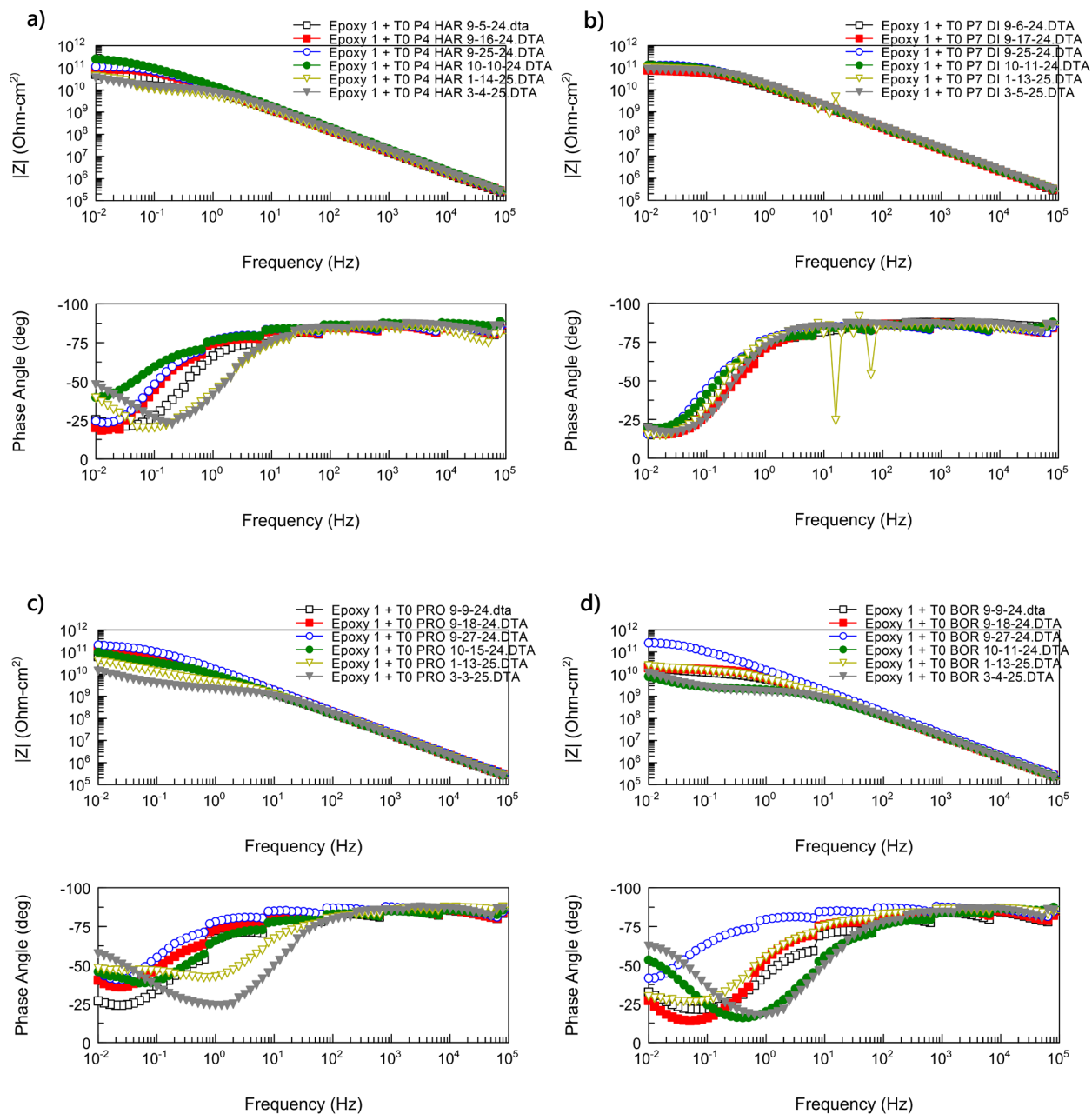


Figure 3. Bode plot of Epoxy 1 + T0, monitored during 5040 hrs of a.) HAR (upper left), b.) DI (upper right), c.) PRO (lower left), d.) BOR (lower right) testing; no spectra flagged as errant.

Epoxy 2 + T0 produced similar results to Epoxy 1 + T0, as shown in Figure 4. The coating system shows similar impedance magnitude at 0.01 Hz. The curves are stable for both HAR and DI water immersion exposures, while more significant changes are seen for PRO and BOR cyclic exposures, likely indicating a more active, corroding system.

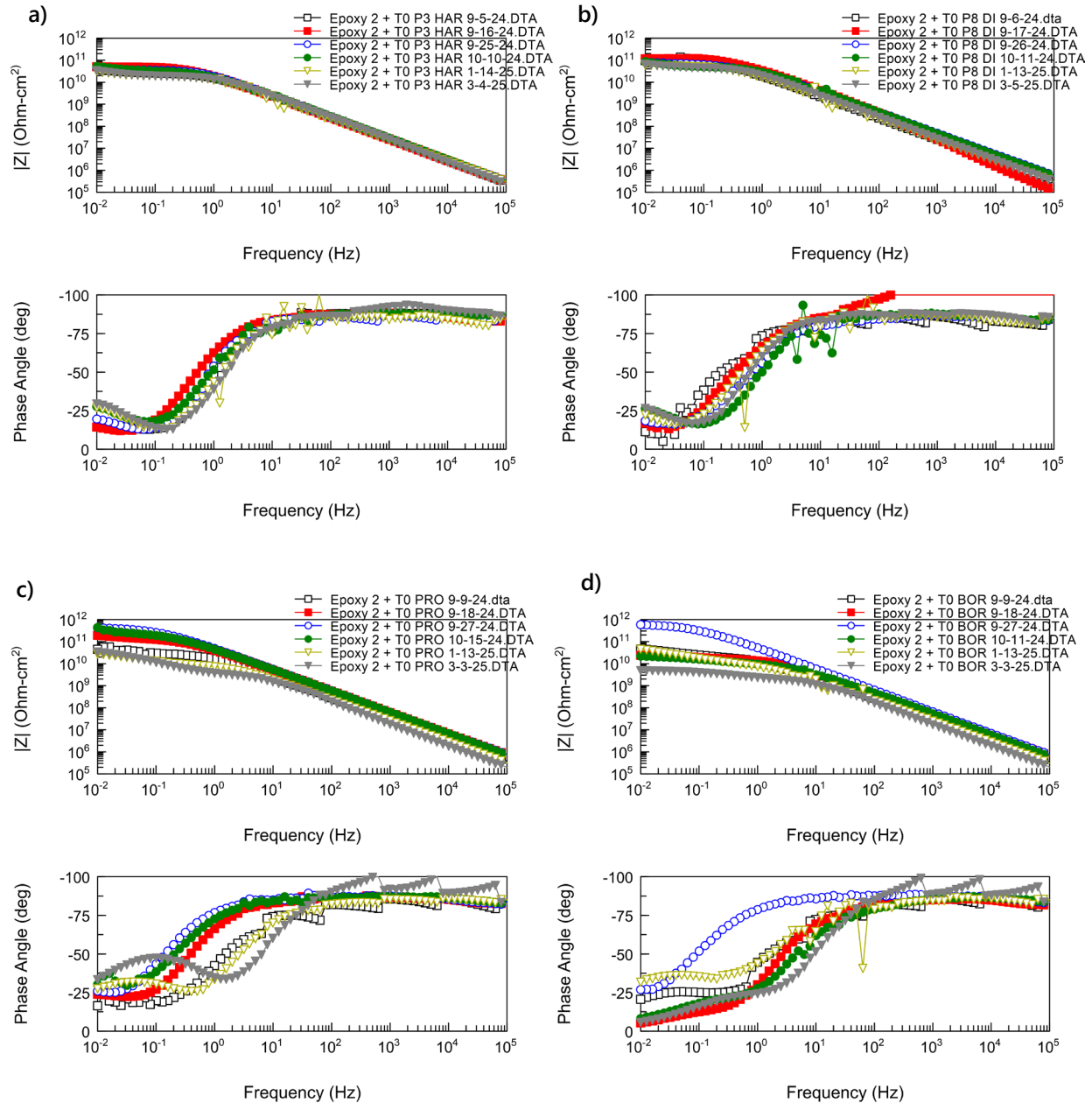


Figure 4. Bode plot of Epoxy 2 + T0, monitored during 5040 hrs of a.) HAR (upper left), b.) DI (upper right), c.) PRO (lower left), d.) BOR (lower right) testing; no spectra flagged as errant data.

4.2.4. Adhesion

Adhesion throughout the entire coating system is essential to prevent the coating system from delaminating in high-velocity water flows and cavitation conditions. There are several adhesion tests to evaluate coatings including pull-off adhesion, peel adhesion, and knife adhesion. Each is performed because the ideal adhesion test to simulate high-velocity water service conditions is unknown. These coating systems will be exposed to long-term water immersion; therefore,

Selecting Primers for Cavitation Resistant Coating Systems

measuring adhesion in both wet and dry conditions is necessary. Failure mechanisms with substrate failures or loss of adhesion of the elastomer could result in large segments delaminating into the service flow, which is not acceptable [22]. Cohesive and glue failures are acceptable modes of failure.

4.2.4.1. Pull-off Adhesion

Pull-off adhesion following ASTM D4541 provides baseline values for the adhesion force required to disbond the coating at a 90-degree pull [11]. Table 3 shows dry and wet adhesion mean pull-off force and standard deviations (St Dev), with most exceeding the 20% glue failure threshold. Dry adhesion is higher than wet adhesion for each coating system, indicating reduced glue cure or bond to the elastomer topcoat. Epoxy 2 + T0 adhesion mechanism changed from glue/ cohesive failure (dry adhesion) to an adhesion failure between the epoxy and the Reclamation adhesive (wet adhesion), shown in Table 3. The 60-percent reduction in force and the failure mode should provide enough evidence to not use Epoxy 2 + T0 in high-velocity water service conditions. PE 1 has a similar trend, changing from 100% glue failure (dry adhesion) to 30% adhesion failure between the epoxy and the manufacturer's adhesive (conditioner) (wet adhesion). Due to the prevalence of glue failures, results are inconclusive and another more reliable test may be required.

Table 3—Wet and dry pull off adhesion strengths of T0 set.

System Name	Pull-off Dry (psi)	ST Dev (psi)	Failure type	Pull-off Wet (psi)	St Dev (psi)	Failure type
PE 1	801	68	100% glue	563	129	70% glue, 30% primer/ adhesive
PE 2	1137	72	100% glue	922	162	100% glue
Epoxy 1 + T0	912	216	Mostly glue, minor cohesive in elastomer	705	287	100% glue
Epoxy 2 + T0	621	334	Mostly glue, minor cohesive in elastomer	370	139	100% primer/ adhesive

4.2.4.2. Peel Adhesion

Peel adhesion can only be done with elastomer topcoats, which bend easily without fracturing. ASTM D429 is used to evaluate the adhesion strength at 90-degree angle of elastomers to a rigid substrate [5]. The test assesses the elastomer to failure until the elastomer either stretches and breaks or propagates along the substrate interface. Failure mechanisms with primer/ substrate failures or loss of adhesion of the elastomer at primer interface are not acceptable in high-velocity water service. It is preferred to have the elastomer stretch and break with no or minimal propagation from the glue line. Figure 5 shows peel strength between wet and dry samples including the maximum force and average force measured over hundreds of data points. The solid pattern indicates the elastomer stretched and tore with minimal propagation (desired), whereas the checkered pattern indicates failure between the epoxy and adhesive with significant propagation (not desired). Epoxy 2 + T0 peeled with minimal force from the substrate after water immersion service. Epoxy 1 + T0 (Original) was repeated, and the second time the force for peel adhesion was lower due to the elastomer being 50% thinner. However, adhesion to the substrate was retained, and the material stretched to nearly 500% elongation before the elastomer broke.

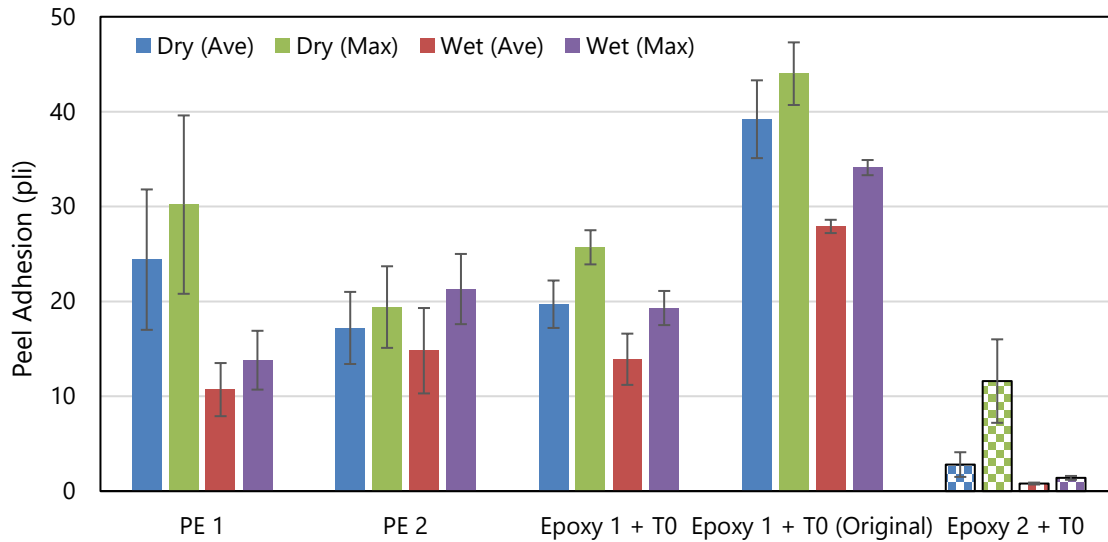


Figure 5. Wet and dry peel adhesion of elastomers to a rigid substrate; solid bars indicate elastomer stretched and tore, and checkered pattern indicates elastomer peeled at epoxy/adhesive interface and propagated.

4.2.4.3. Wet Knife Adhesion

Knife adhesion following ASTM D6677 was only performed after water immersion service, to determine if the coating can be peeled from the substrate or primer [12]. Chip sizes removed during the knife adhesion test provides the coating system a ranking. Small chips or coatings that can't be lifted earn a high score (10), showing strong adhesion. Large chips or easy peeling get a low score (2), showing weak adhesion. Table 4 shows the knife adhesion results of each coating system.

Table 4.—Wet knife adhesion of coatings

System Name	Rating	Notes
PE 1	10	Could not remove elastomer
PE 2	10	Could not remove elastomer
Epoxy 1 + T0	10	Could not remove elastomer
Epoxy 2 + T0	2	T0 peels from epoxy 2 and adhesive

Adhesion test results indicated potential issues when Epoxy 2 + T0 are used in environments with high-velocity water immersion. T0 elastomer might delaminate from the Epoxy 2 primer due to this observed ease of removal between the elastomer and primer. These test results show the importance of adhesion within the entire coating system to prevent rapid failure under cavitation conditions.

4.2.5. Rapid Deformation Direct Impact

Macroscopic damage from large debris is a different type of impact damage compared to the cavitation impact. Direct impact testing evaluates when coating damage occurs from rapid

deformation on a macroscopic level. The cavitation resistant coatings exhibited low impact resistance except for PE 2 having 90 in-lbs and Epoxy 2 + T0 exceeded the maximum impact of the test apparatus, shown in Table 5.

Table 5.—Direct impact of coating systems

System Name	Average Force (in-lbs)
PE 1	60
PE 2	90
Epoxy 1 + T0	30
Epoxy 2 + T0	320

4.2.6. Cathodic Disbondment

Cathodic disbondment assesses coating damage from overpotential from a cathodic protection system. This procedure produces hydroxide (strong base) at the defect and sometimes disrupts adhesion mechanisms, causing coating disbondment. While cathodic protection may not be installed in high-velocity water immersion service conditions, end-users may use these coating systems in different conditions where cathodic protection is used, and it is important to understand the limitations. Table 6 shows T0 elastomer completely disbonded from Epoxy 2, due to water immersion causing loss of adhesion for Epoxy 2 + T0. This outcome is consistent with the adhesion test results in the previous sections. PE2 and Epoxy 1 + T0 had acceptable levels of disbondment. PE1 was not tested.

Table 6.—Cathodic disbondment results

System Name	Disbondment Radius (inches)	Notes
PE 1	N/A	Not tested
PE 2	0.37	Disbondment area was not a circle and was irregular. Elastomer adhered to epoxy
Epoxy 1 + T0	0	No disbondment, elastomer and epoxy well adhered
Epoxy 2 + T0	0	No disbondment of epoxy, 0.6-inch disbondment was between epoxy and elastomer. Could peel the entire elastomer from the epoxy

4.2.7. Slurry Erosion

Erosion control from particulates in high-velocity water immersion has been one of the most challenging service conditions to overcome. Many metals and coatings do not perform well, and typically specialized metals and coatings are required to control slurry erosion. Coating manufacturers have ceramic filled epoxies and more recently polyurethane technologies for erosion control but still result in wear rates and material loss. Our studies compared different metals to cavitation resistant coatings.

Figure 6 shows the erosion resistance of various materials. Mild steel had the highest erosion rate, exceeding 70 microns per 96-hr test. Stainless steel 304 lost approximately 5 microns and is a typical metal used for moderate to severe erosion control. PE 1 and PE 2 were slightly better than stainless steel 304 at approximately 4- and 1-micron loss, respectively. Epoxy 1 + T0 and Epoxy 2 + T0 results were combined to obtain more replicates in performance for T0 elastomer. T0 elastomer was comparable to PE 1 and PE 2 at 2-micron loss. The polyurethane coating systems are resilient and mitigate erosion as good as stainless steel 304. It would be lower cost to replace coatings periodically than replace metal structures if service conditions cause severe erosion or switch to an expensive metal.

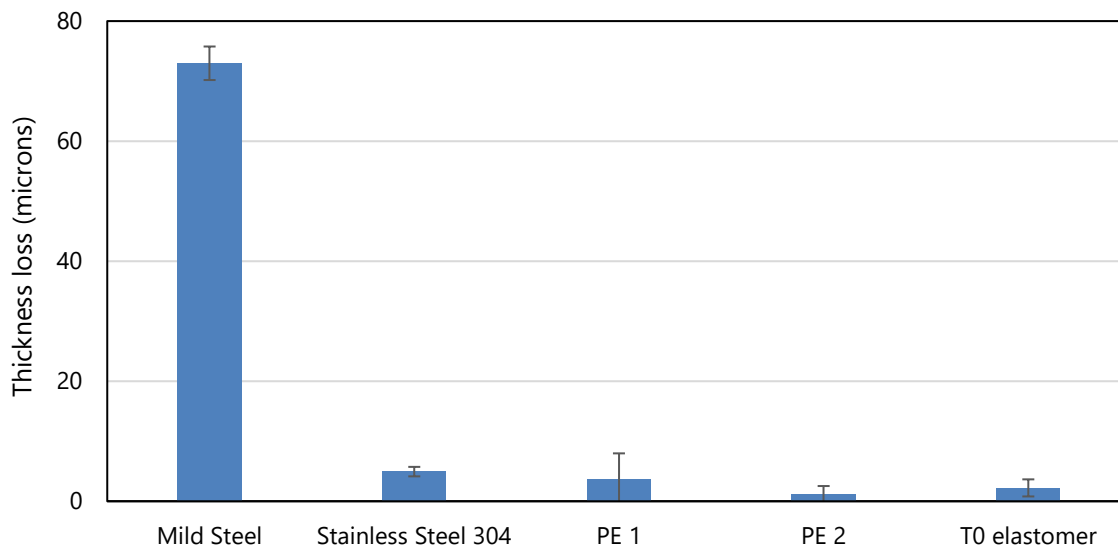


Figure 6. Erosion rates of steel, stainless steel 304, PE 1, PE 2, T0 elastomer.

4.2.8. Cavitation

Historically, Reclamation's experience with coatings for cavitation resistance has been unsatisfactory, typically only applied in the draft tube (below the turbine runner). These coatings usually fail within the first few feet below the turbine runner, before the cavitation intensity diminishes to manageable intensity for commercially available cavitation resistant coatings. The need to find better cavitation resistant coatings was the long-term goal. Existing standard test procedures are designed to evaluate metals, not coatings. Therefore, S&T project 8542 developed a new cavitation test procedure to evaluate both. Because a new test procedure was developed, correlations to field performance are not yet available.

Initial test parameters were set at a cavitation intensity that damage mild steel to a measurable metal loss but causes stainless steel 304 minimal metal loss. Table 7 shows the onset of damage and volume of metal loss after 200 hrs of testing for mild steel and stainless steel 304. Stainless steel has about 10 times less volumetric metal loss than mild steel.

Table 7.—Cavitation of metals using the new Reclamation cavitation testing procedure.

Material	Onset Damage (hrs)	Extent of Damage after Duration
Mild Steel	24	140 mm ³ after 200 hrs
Stainless Steel 304	144	13 mm ³ after 216 hrs

Conventional corrosion resistant coatings failed to substrate within two hrs (not shown). Many commercially available cavitation resistant coatings failed within 8 hrs, well before mild steel damage was observed [1]. The best commercially available cavitation resistant coatings, PE 1 and PE 2, failed within 200 hrs, with onset damage at 100 and 180 hrs, respectively, as observed in Figure 7. Epoxy 1 + T0, the Reclamation developed T0 elastomer, had an onset damage approximately after the same exposure time as PE 1 and PE 2, but required four times longer to damage the coating down to the substrate. However, Epoxy 2 + T0 damaged quickly under cavitation conditions. The onset damage was not captured because it had already occurred by the first data collection taken after 3 hrs of exposure. It is believed that the reduced adhesion of the Epoxy 2 + T0 system, as observed in adhesion and cathodic disbondment testing, caused this quick failure to the substrate. This result shows the importance of a complete system with adequate adhesion throughout and that adhesion testing, specifically peel adhesion, is the ideal pre-screening test method for optimized cavitation resistant coatings in Section 5.0.

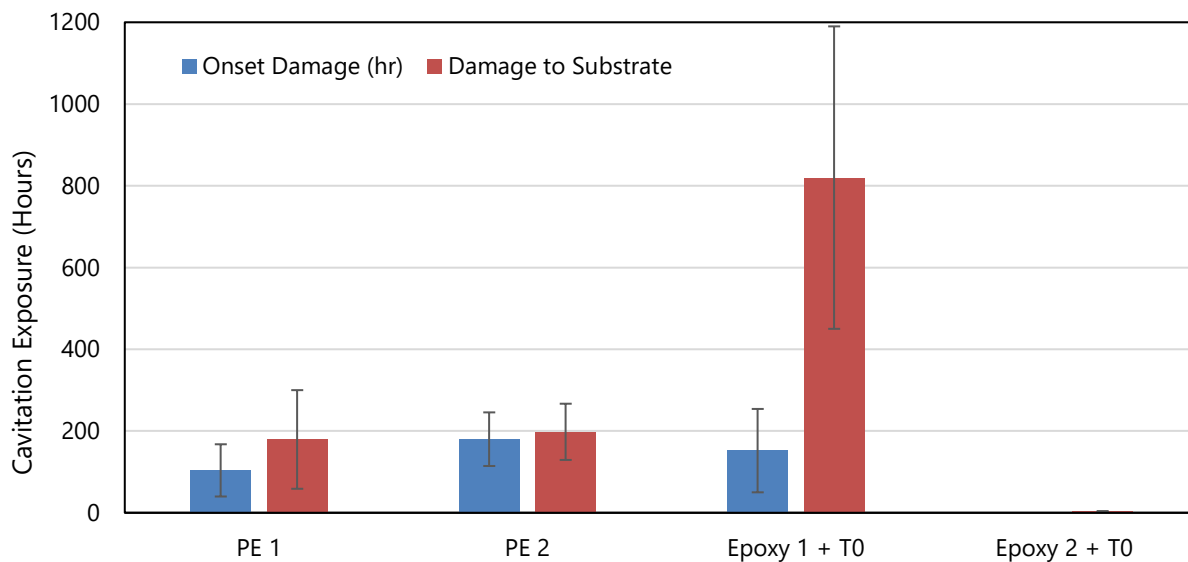


Figure 7. Cavitation resistance of coatings PE 1, PE 2, Epoxy 1 + T0, and Epoxy 2 + T0.

4.3. Summary and Next Steps

Corrosion resistance testing showed PE 1, PE 2, Epoxy 1 + T0, and Epoxy 2 + T0 to provide adequate undercutting resistance for cyclic and water immersion. A side-by-side comparison for each primer with and without the optimized T4.5 formulation will inform any benefits for undercutting performance and better understanding of the resistive behavior observed in EIS (see next section).

The testing shows the Reclamation Epoxy 1 + T0 coating system to be comparable to the best commercially available products, with better cavitation and erosion resistance than mild steel. However, the results showed that adhesion is required throughout the coating system, or the T0 elastomer will fail quickly in cavitation, as observed with Epoxy 2 + T0.

Comparing results across the different adhesion test procedures, peel adhesion had the most conclusive, quantitative data with correlation to the cavitation results. Therefore, peel adhesion was selected for pre-screening additional primer systems for the optimized T4.5 cavitation resistant coating formulations.

5.0 Primer Selection for Optimized T4.5 Elastomer Systems

5.1. Pre-screening (Peel Adhesion)

It is vital that cavitation resistant coating systems stay adhered to the structure in high-velocity water to be successful in hydropower applications. Peel adhesion testing was determined to provide the most reliable test result for correlation to cavitation performance (see Section 4). Therefore, peel adhesion is used to screen various primers to develop complete coating system options with superior durability and longevity in dry and wet conditions. The goal is to identify commercially available primers or coating systems that are compatible with the optimized cavitation resistant coating to deploy as a complete system. The pre-screening evaluated ten epoxy primers, two vinyl systems, one moisture cured urethane (MC urethane), and three polysiloxanes all utilizing Reclamation's optimized T4.5 formulation. Refer to Table 2 in Section 2 to see the full list of coating types and code names.

Failure mechanisms within the primer/substrate or loss of adhesion of the elastomer at the primer interface are not acceptable in high-velocity water service. It is preferred to have the elastomer stretch and break with no or minimal propagation from the glue line.

The peel adhesion results in Figure 8 show that most primers with the Reclamation T4.5 topcoat do not form adequate wet peel adhesion within the one week curing schedule, indicated by the checkered pattern. Four coating systems provided good dry and wet adhesion with the T4.5 elastomer: Epoxy 1, Polysiloxane 1, Vinyl System 5EZ, and Epoxy 10. The remaining coating

systems did not obtain good dry and wet adhesion. However, Vinyl System 4 and Epoxy 9 experienced failure at the steel substrate (striped pattern), meaning the T4.5 elastomer adhered well to the primer. Wet adhesion failure at the steel interface of Vinyl System 4 was resolved with the zinc-rich primer, Vinyl System 5EZ, which produced an acceptable failure mode. To resolve the poor wet adhesion for Epoxy 9, a small amount of solvent was added to the epoxy and given code name Epoxy 10.

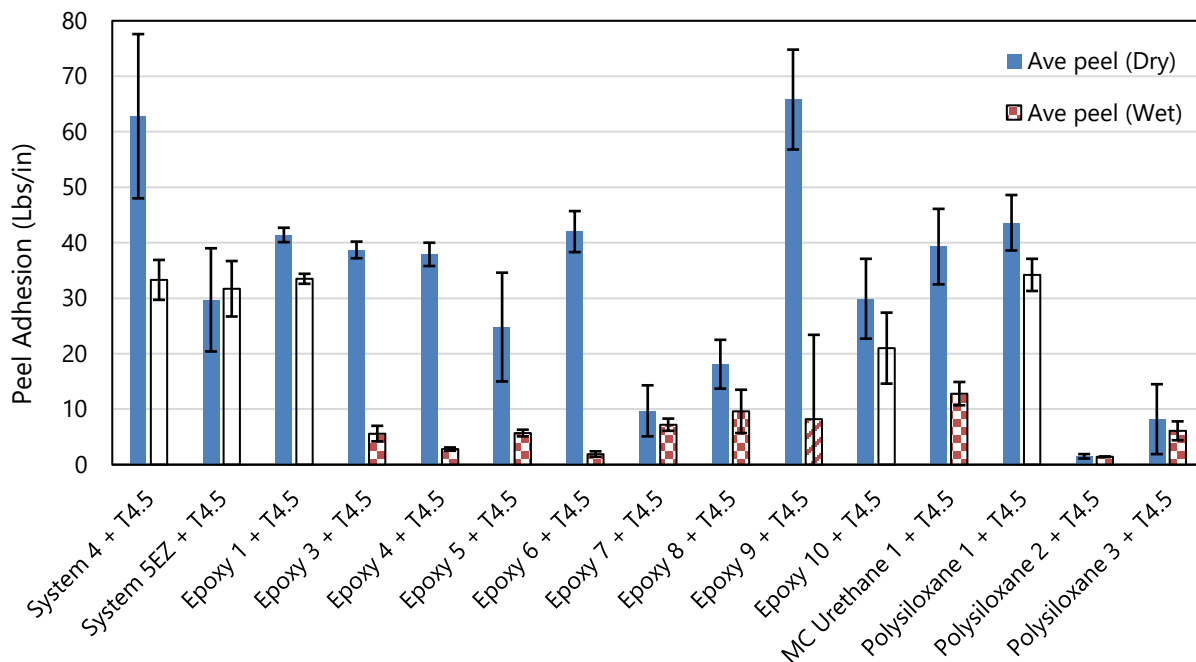


Figure 8. Pre-screened primer results using peel adhesion testing; wet adhesion failed to substrate is indicated by a striped pattern; primer/ adhesive failure is indicated by the checkered pattern; and solid bars indicate elastomer stretched and stayed adhered.

The selected primers for corrosion protection evaluation were Vinyl System 5EZ, Epoxy 1, and Polysiloxane 1. Additionally, Vinyl System 4, Epoxy 3, and Epoxy 4 were selected as negative controls to confirm that wet and dry peel adhesion are correlating as expected for cavitation performance. The peel adhesion results for Epoxy 9 and Epoxy 10 were not obtained in time to prepare panels for this round of testing, and both would be valuable future testing.

5.2. Surface Preparation and Coating Application of Selected Systems

All samples were prepared using A36 carbon steel. Surface preparation for all panels consisted of removing oil and contaminants by detergent cleaning following SSPC-SP1. Once panels were cleaned, they were abrasive blast cleaned to SSPC-SP 5/NACE 1 with an angular profile of 3.0 mils. Reclamation applied commercially available coatings in accordance with coating manufacturers' instructions. Each coating system had a set of twenty-four 3 in. x 6 in. x 1/8 in.

steel coupons, two 11-in. diameter x 1/8-in. thick round disks, and one 3-in. diameter x 1-foot section of pipe. All coating systems were cured for at least one week.

5.2.1. Epoxy 1 – Reclamation T4.5 Cavitation Resistant Coating Systems (Epoxy 1 + T4.5)

Three coats of corrosion resistant Epoxy 1 were sprayed at 4-6 mils per coat for a total of 12-18 mils DFT. After the final coat was cured for 12-24 hrs, the Reclamation adhesive was brush applied to Epoxy 1 without additional surface preparation. The adhesive was cured for 2 hrs. Reclamation T4.5 elastomer was applied at 15-20 mils DFT, and a second coat was applied 2 hrs after the first T4.5 coat was roller applied for a total of 30-40 mils of elastomer.

5.2.2. Epoxy 3 - Reclamation T4.5 Cavitation Resistant Coating Systems (Epoxy 3 + T4.5)

Three coats of Epoxy 3 were sprayed at 4-6 mils per coat for a total of 12-18 mils DFT. After the final coat was cured for 12-24 hrs, the Reclamation adhesive was brush applied to Epoxy 3 without additional surface preparation. The adhesive was cured for 2 hrs. Reclamation T4.5 elastomer was applied at 15-20 mils DFT, and a second coat was applied 2 hrs after the first T4.5 coat was roller applied for a total of 30-40 mils of elastomer.

5.2.3. Epoxy 4 - Reclamation T4.5 Cavitation Resistant Coating Systems (Epoxy 4 + T4.5)

Three coats of Epoxy 4 were sprayed at 4-6 mils per coat for a total of 12-18 mils DFT. After the final coat was cured for 12-24 hrs, the Reclamation adhesive was brush applied to Epoxy 4 without additional surface preparation. The adhesive was cured for 2 hrs. Reclamation T4.5 elastomer was applied at 15-20 mils DFT, and a second coat was applied 2 hrs after the first T4.5 coat was roller applied for a total of 30-40 mils of elastomer.

5.2.4. Polysiloxane 1 - Reclamation T4.5 Cavitation Resistant Coating Systems (Polysiloxane 1 + T4.5)

Two coats of Epoxy 1 were sprayed at 4-6 mils per coat for a total of 8-12 mils DFT, and one coat of Polysiloxane 1 was sprayed at 4-6 mils for a total system of 12-18 mils DFT. After the final coat was cured for 12-24 hrs, the Reclamation adhesive was brush applied to Polysiloxane 1 without additional surface preparation. The adhesive was cured for 2 hrs. Reclamation T4.5 elastomer was applied at 15-20 mils DFT, and a second coat was applied 2 hrs after the first T4.5 coat was roller applied for a total of 30-40 mils of elastomer.

5.2.5. USACE Vinyl System 4 - Reclamation T4.5 Cavitation Resistant Coating Systems (System 4 + T4.5)

Five double spray coats of USACE V-766E were sprayed at 1.5-2.0 mils per double spray coat for a total of 7.5-10 mils DFT. After the final coat was cured for 12-24 hrs, the Reclamation adhesive was brush applied to V-766E without additional surface preparation. The adhesive was cured for 2 hrs. Reclamation T4.5 elastomer was applied at 15-20 mils DFT, and a second coat was applied 2 hrs after the first T4.5 coat was roller applied for a total of 30-40 mils of elastomer.

5.2.6. USACE Vinyl System 5EZ - Reclamation T4.5 Cavitation Resistant Coating Systems (System 5EZ + T4.5)

One double spray coat of USACE VZ-108d was applied at 2-3 mils DFT of zinc-rich primer. Four double spray coats of USACE V-766E were sprayed at 1.5-2.0 mils per double spray coat for a total of 8-11 mils DFT. After the final coat was cured for 12-24 hrs, the Reclamation adhesive was brush applied to V-766E without additional surface preparation. The adhesive was cured for 2 hrs. Reclamation T4.5 elastomer was applied at 15-20 mils DFT, and a second coat was applied 2 hrs after the first T4.5 coat was roller applied for a total of 30-40 mils of elastomer.

5.3. T4.5 Elastomer Results

5.3.1. Water immersion

Figure 9 shows the undercutting resistance of the coating systems evaluated in HAR and DI water immersion with the scale adjusted for direct comparison to Section 5.3.2. Cyclic Exposure. All primers with and without T4.5 elastomer provided good or excellent undercutting resistance, less than 1/8 in. HAR exposure was more aggressive than DI water immersion, but the undercutting was minor with all systems—as demonstrated with all values near 0.0 in. on the plot. Vinyl System 5EZ with and without T4.5 elastomer was the best performing primer system, possibly due to the zinc rich primer. There does not appear to be significant difference between primers without and with the T4.5 elastomer. An exception is Epoxy 1 + T4.5, which had the largest undercutting increase when adding the T4.5 topcoat in HAR at 0.04 in., which is still far below the good criteria (0.125 in.). No blistering or cracking was observed on any of the coating systems test panels. Barrier properties were measured using EIS on two identical panels for each coating system without and with T4.5 elastomer.

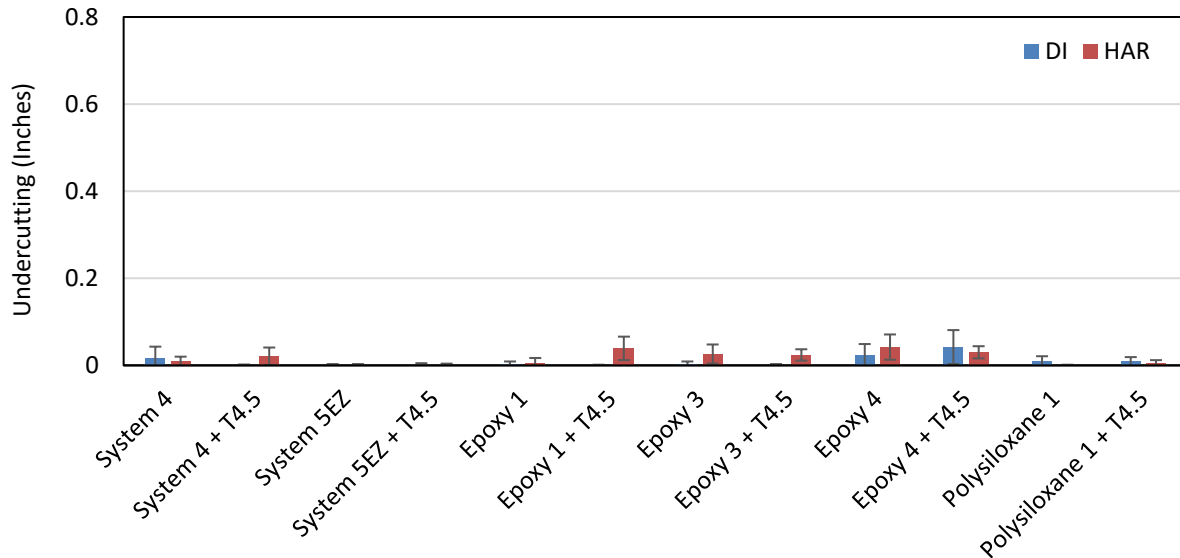


Figure 9. Undercutting resistance of selected primer systems comparing with and without the optimized T4.5 cavitation resistant coating in DI and HAR water immersion; bars not visible are 0.0 in.; scaled to a maximum of 0.8 in. for direct comparison to cyclic exposure results.

Vinyl System 4—with and without T4.5 elastomer topcoat—had visible small black specks across the steel interface after the coating was removed for the corrosion undercutting evaluation. System 4 contains 0.2% phosphoric acid; it is plausible that black specks are iron phosphate or iron oxide/ hydroxides. Further investigation is warranted.

5.3.2. Cyclic Exposure

Figure 10 compares the undercutting performance of the primers with and without T4.5 elastomer. Vinyl System 5EZ was the best performing complete system, rated as good except for the FOG cyclic exposure that rated excellent (see criteria in Appendix A). The coatings systems that provided acceptable undercutting results were Vinyl System 4 and Vinyl System 5EZ (with and without T4.5 elastomer), Epoxy 3, and Polysiloxane 1, each with a mean value less than 1/4-in. undercutting in at least two of the cyclic tests, PRO, BOR, and FOG.

Epoxy 1 and Epoxy 3 with the T4.5 elastomer topcoat had worse undercutting compared to the primer alone and received a poor rating with greater than 1/2 in. undercutting. The T4.5 elastomer absorbs water more than the primers, resulting in significant internal stress, due to water uptake (swelling) and drying (shrinking) compared to the primers during cyclic exposure. It is believed that T0 has lower internal stress than T4.5 since it was a thermoplastic polyurethane. Or it's because the primer systems are highly crosslinked coatings and are susceptible to undercutting when an external force (the elastomer topcoat) is pulling on the primer. Based on these results it is not recommended to use the T4.5 elastomer in fluctuating immersion service conditions. Epoxy 4 results were poor with and without the topcoat. Two replicates were used for undercutting resistance; additional replicates could reduce the variability observed in the data.

Selecting Primers for Cavitation Resistant Coating Systems

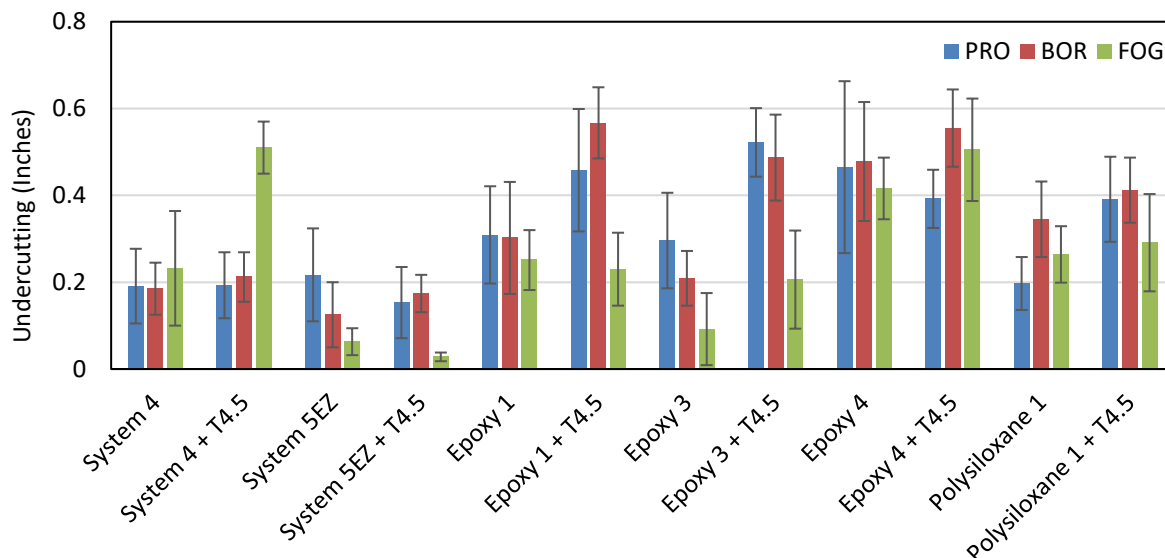


Figure 10. Undercutting resistance of down selected primer systems comparing with and without the optimized T4.5 cavitation resistant coating in PRO, BOR, and FOG cyclic exposure.

The results obtained for Vinyl System 4 and Vinyl System 5EZ with the T4.5 elastomer topcoat suggest that it could be added to control erosion or cavitation in fluctuating immersion service. The performance may stem from these primer systems being thermoplastic coatings with low internal stress. However, the T4.5 elastomer severely yellows in UV conditions, reducing the aesthetic value in outdoor exposure.

5.3.3. Electrochemical Impedance Spectroscopy

All primer systems with and without T4.5 elastomer were evaluated for barrier properties using EIS. The body of the report presents and discusses best-performing systems and exposures; the remaining EIS results are provided in Appendix D.

Figure 11 compares EIS spectra of Vinyl System 5EZ with and without the T4.5 elastomer, for HAR and DI water immersion and PRO cyclic exposures. With no elastomer, Vinyl System 5EZ shows excellent barrier properties with primarily capacitive behavior (Figure 11 a, c, and e). With the T4.5 elastomer topcoat, the data has resistive behavior with a minimum (peak) between 1 and 0.1 Hz that is consistent with a smaller resistor, likely the T4.5 elastomer pore resistance, in series with a larger resistor (Figure 11 b, d, and f). Peak movement to higher frequencies equates to lower values for a resistor. The phase angle value at 0.01 Hz is similar with and without the topcoat for each exposure meaning the elastomer topcoat does not reduce corrosion protection.

Note the dates showing inconsistent spectra, compared to the other datasets, within Figure 11 c) 6-29-26, d) 5-20-26, and f) 6-29-26. This is suspected to be the result of a data collection error, which also occurred for other systems on the same dates. The data is retained in these plots for completeness but flagged as likely errant, such as due to a non-functional reference electrode. Four potentiostats and test setups were used to collect EIS data.

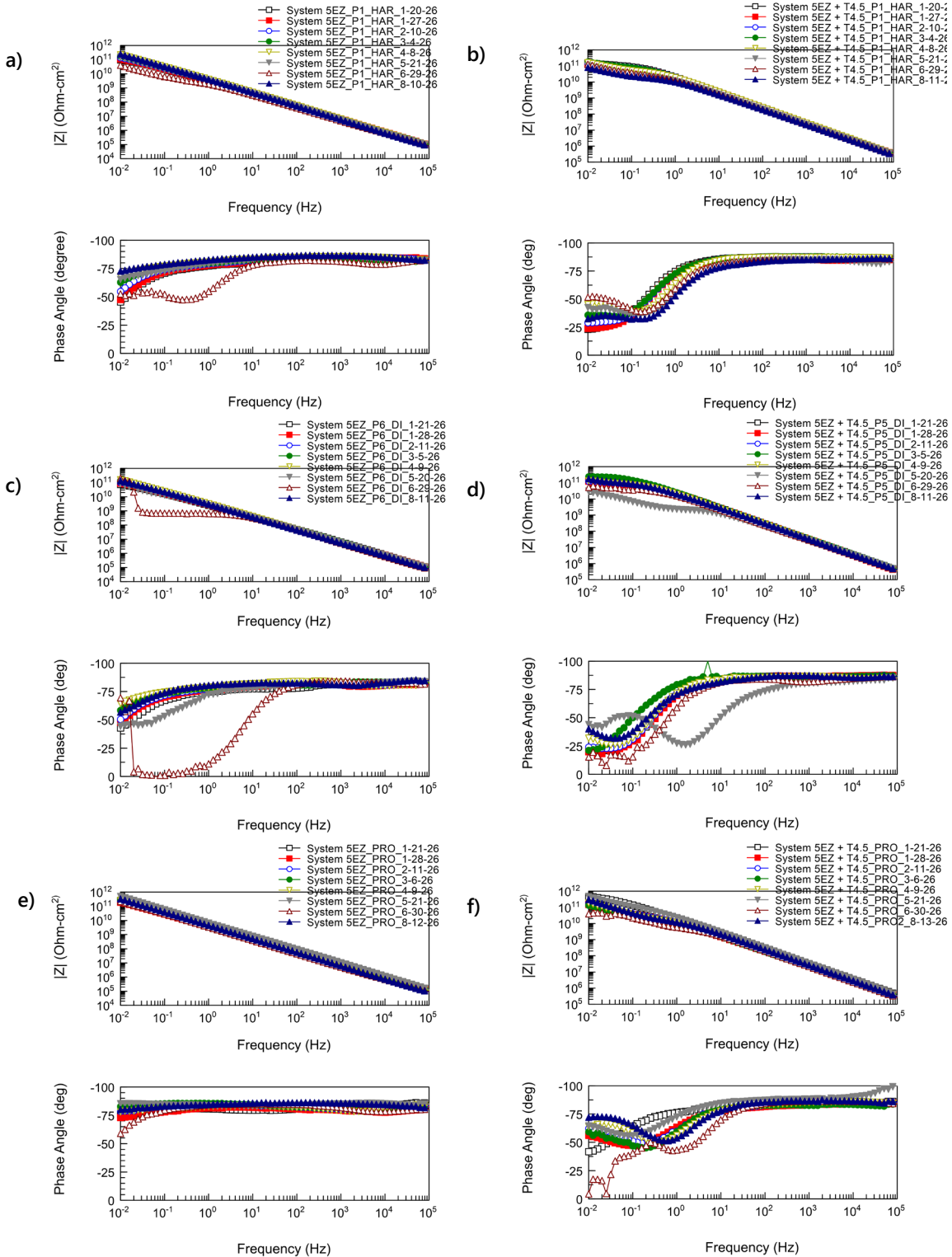


Figure 11. EIS of Vinyl System 5EZ a) in HAR without and b) with T4.5 elastomer, c) in DI without and d) with T4.5, and e) in PRO with and f) without T4.5. 5-21-26 and 6-29-26 flagged as errant data in some plots.

Selecting Primers for Cavitation Resistant Coating Systems

Figure 12 compares EIS spectra of Epoxy 1 with and without the T4.5 elastomer, for HAR and DI water immersion and PRO and BOR cyclic exposures. Epoxy 1 had moderate barrier properties in HAR and DI water immersion with primarily resistive behavior, i.e., corrosion, that is stable (Figure 12 a and c). Corrosion activity is reduced in PRO cyclic exposure but is again stable (Figure 12 e). Much like Vinyl System 5EZ, the addition of the elastomer topcoat, Epoxy 1 + T4.5, results in a porous, smaller resistor behavior with a minimum (peak) between 1 and 0.1 Hz and pronounced changes in the magnitude of this resistor value across the experiment (Figure 12 b, d, and f).

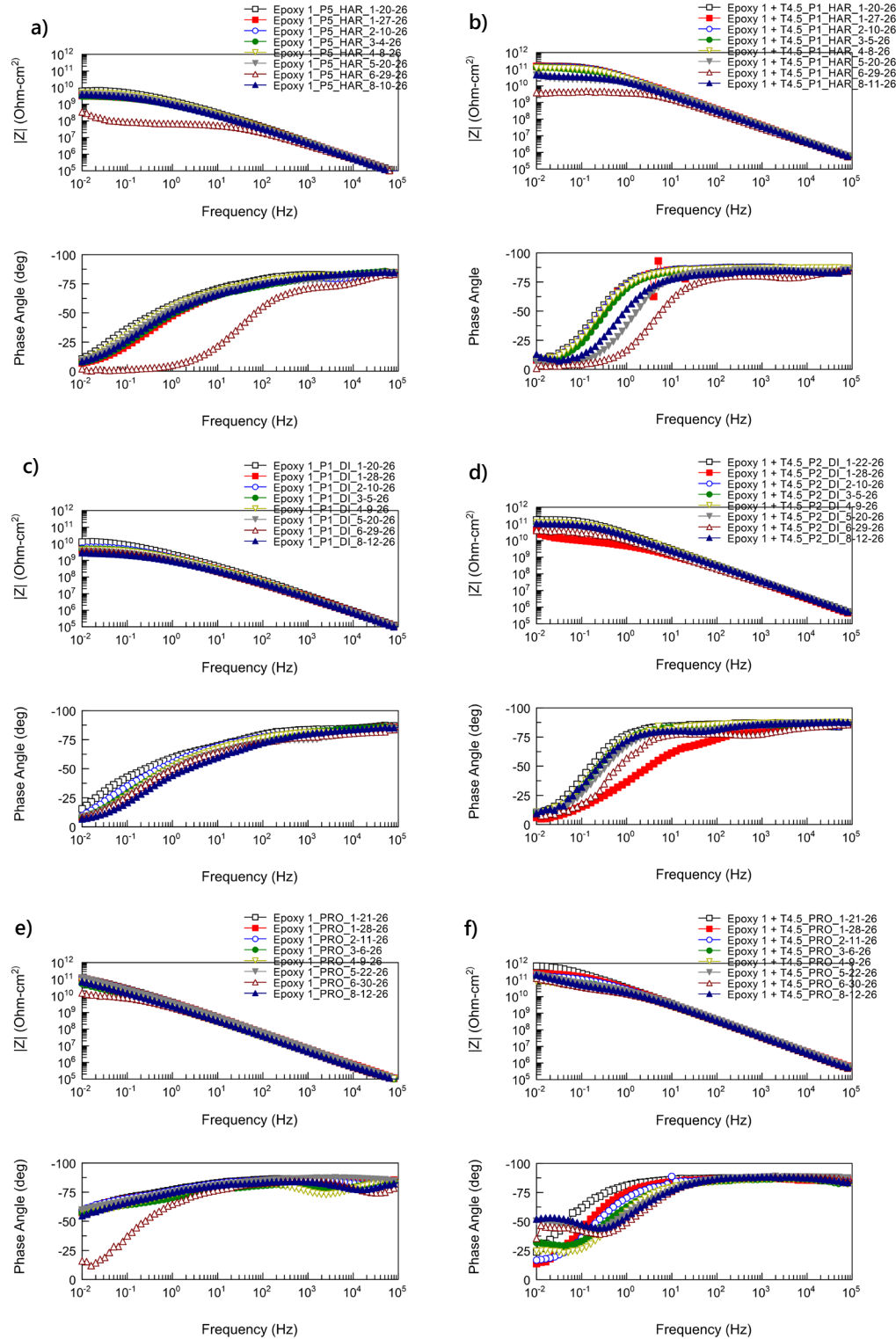


Figure 12. EIS of Epoxy 1 a) in HAR without and b) with T4.5 elastomer, c) in DI without and d) with T4.5, and e) in PRO with and f) without T4.5; DI without. 1-28-26 and 6-29-26 flagged as errant data in a couple plots.

Figure 13 compares EIS spectra of Polysiloxane 1 with and without the T4.5 elastomer, for HAR and DI water immersion and PRO and BOR cyclic exposures. Polysiloxane 1 had excellent barrier properties in HAR and DI water immersion with primarily capacitive behavior and good stability with minimal degradation (Figure 13 a and c). Polysiloxane 1 in PRO cyclic exposure is similar, but the spectra show some degradation occurring at low frequencies (Figure 13 e). Addition of the elastomer topcoat, Polysiloxane 1 + T4.5, produces nearly identical behavior to that observed for Vinyl System 5EZ and Epoxy 1, helping to confirm the unique, low resistance features attributed to the T4.5 elastomer (Figure 13 b, d, and f). The PRO cyclic exposure provides a more verifiable example of the resistor magnitude decreasing over the exposure time, i.e., decreased pore resistance of the elastomer. The EIS testing confirmed that addition of the elastomer does not reduce corrosion protection in water immersion exposures Polysiloxane 1.

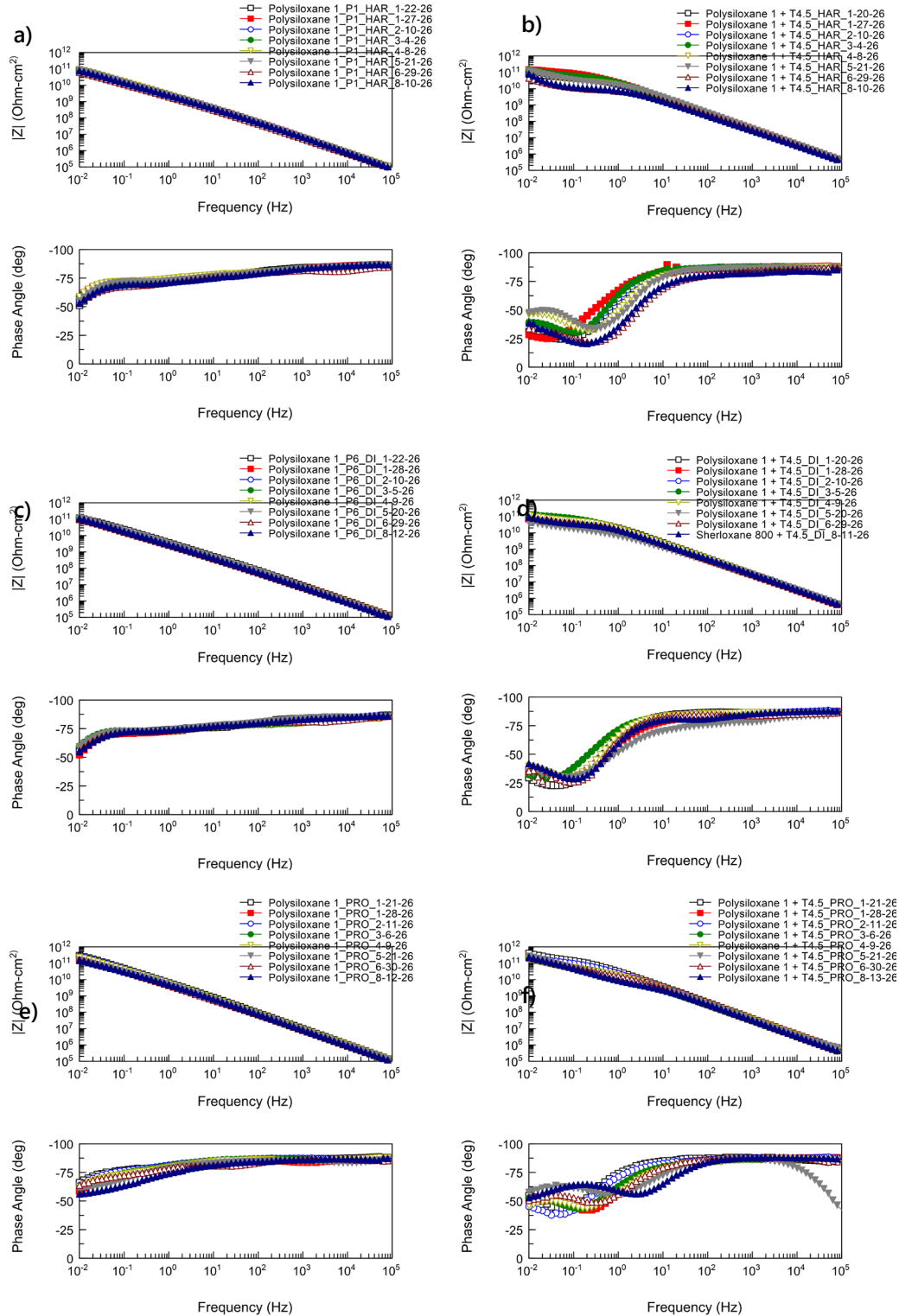


Figure 13. EIS spectra of Polysiloxane 1 in HAR without a) and with T4.5 b), DI without c) and with d), and PRO without e), and with f) monitored for 5040 hrs.

Selecting Primers for Cavitation Resistant Coating Systems

The remaining primer systems with and without T4.5 elastomer can be found in Appendix D. Vinyl System 4 is like Vinyl System 5EZ, with resistive behavior due to T4.5 elastomer pores. Epoxy 3 and Epoxy 4 show primer degradation and T4.5 elastomer pore resistance changes.

5.3.4. Adhesion

Peel adhesion was shown to best correlate to cavitation performance and was used as a pre-screening method. However, pull off adhesion and knife adhesion were collected to verify the information in Section 4.

5.3.4.1. Pull-off Adhesion

The pull-off adhesion results for the primer with and without T4.5 elastomer are shown in Table 8. As seen in Section 4, the results are inconclusive with a significant number of glue failures and varying failure modes. The adhesion results for this set are within one standard deviation. For instance, Epoxy 3 had poor dry and wet adhesion and failed at the substrate, while Epoxy 3 + T4.5 had elastomer failure in dry adhesion and glue failures in wet adhesion at similar values as Epoxy 3.

Table 8 –Wet and dry pull off adhesion for selecting primers for T4.5 cavitation resistant coating

System Name	Pull-off Dry (psi)	ST Dev (psi)	Failure type	Pull-off Wet (psi)	St Dev (psi)	Failure type
System 4	1976	261	100% glue	843	174	60% glue 40% substrate
System 4 + T4.5	1322	192	50% primer/adhesive 50% elastomer	932	205	30% glue 30% primer/ adhesive 30% substrate 10% elastomer
System 5EZ	1605	177	100% glue	1418	183	80% glue 20% cohesive in V-766E
System 5EZ + T4.5	1336	100	100% cohesive in V-766E	905	275	100% glue
Epoxy 1	867	159	85% glue 15% epoxy	727	202	50% glue 40% epoxy 10% substrate
Epoxy 1 + T4.5	832	81	70% epoxy 30% elastomer	587	254	100% glue
Epoxy 3	1282	250	70% substrate 30% cohesive in epoxy	989	258	100% substrate
Epoxy 3 + T4.5	1358	97	70% elastomer 30% primer/ adhesive	965	213	100% glue
Epoxy 4	1495	46	75% epoxy 25% glue	1393	263	50% glue 50% epoxy
Epoxy 4 + T4.5	1306	93	100% glue	981	129	80% glue 20% elastomer
Polysiloxane 1	992	177	100% epoxy primer	947	156	90% epoxy primer 10% substrate
Polysiloxane 1 + T4.5	824	71	50% epoxy primer 50% elastomer	1025	259	100% glue

5.3.4.2. *Peel Adhesion*

Peel adhesion results are shown in pre-screening data from Section 5.1, in Figure 8.

5.3.4.3. *Wet Knife Adhesion*

The knife adhesion rating with the T4.5 elastomer generally increased because the elastomer is not brittle and doesn't chip compared to the primer alone, observed in Figure 14. These results differ from the pull-off and peel adhesion results. The exception is for Vinyl System 4 + T4.5 where the primer system failed at the substrate with minimal force and strips greater than 30 mm lifted, consistent with previous results indicating concern for complete delamination in high-velocity water immersion.

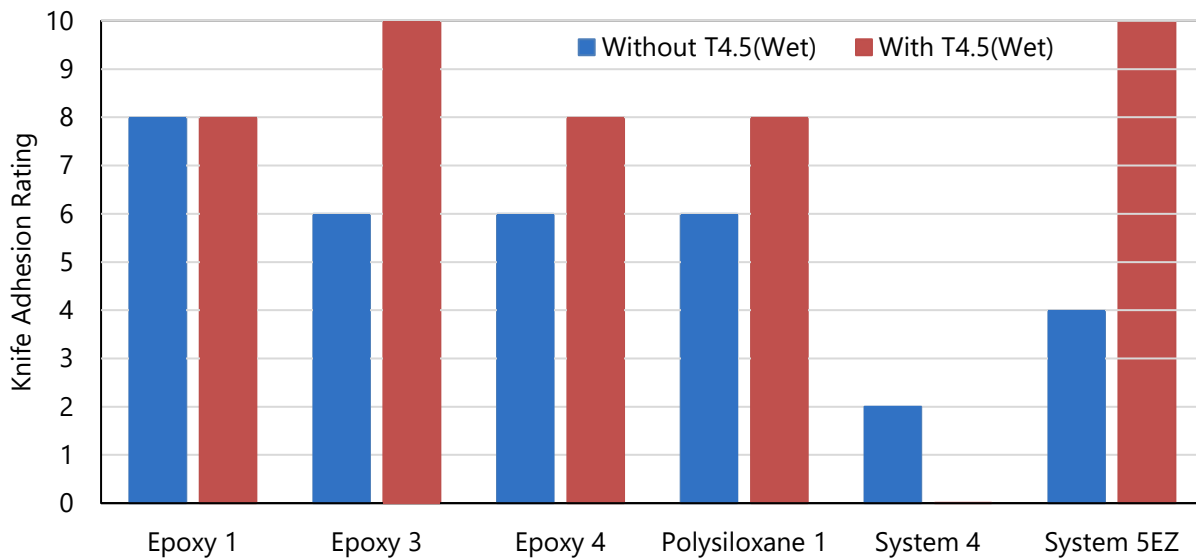


Figure 14. Wet knife adhesion for the primer selection data set

5.3.5. Rapid Deformation Direct Impact

The T4.5 elastomer impact force is recorded as the force to only penetrate the elastomer, damage to the substrate has not occurred. The impact resistance for the primers is the force to fail the coating to the substrate. The results are highly variable, shown in Table 9, with the T4.5 elastomer at times requiring less force to fail compared to the epoxy primer and other times requiring greater force. Vinyl System 4 + T4.5 was not evaluated due to not having enough samples. The lowest impact force for a primer was Vinyl System 4. The highest impact resistance was for Vinyl System 5EZ. The T4.5 cavitation resistant coating showed to have the best impact resistance with Vinyl System 5EZ, followed by Epoxy 1.

Table 9.—Impact resistance of the primer selection coating systems data set.

System Name	Force (In-lbs)	Notes
Epoxy 1	50	cracked
Epoxy 1 + T4.5	85	Failed within elastomer, epoxy did not crack
Epoxy 3	70	cracked
Epoxy 3 + T4.5	44	Failed within elastomer, epoxy did not crack
Epoxy 4	58	cracked
Epoxy 4 + T4.5	36	Failed within elastomer, epoxy did not crack
Polysiloxane 1	80	Cracked
Polysiloxane + T4.5	42	Failed within elastomer, polysiloxane did not crack
System 4	40	Plastic deformation
System 4 + T4.5	N/A	Failed within elastomer, vinyl did not crack
System 5EZ	160	Plastic deformation
System 5EZ + T4.5	100	Failed within elastomer, vinyl did not crack

5.3.6. Cathodic Disbondment

Table 10 shows the cathodic disbondment results for the selected primer data set. USACE Vinyl System 4 and Vinyl System 4 + T4.5 exhibited poor cathodic disbondment resistance which could be attributed to poor wet adhesion. System 4 with and without T4.5 could be completely removed from the substrate and had corrosion specks under the coating, as observed previously. Epoxy 3 blistered randomly across the entire pipe surface, and had a disbondment radius of 2.25 in., while with T4.5 had no blistering and only a 0.5-in. disbondment radius. Vinyl System 5EZ showed slight improvement with T4.5 elastomer from 0.75-in. to 0.5-in. radius. Epoxy 1 also showed a slight improvement with the T4.5 elastomer from 0.4 in. to 0.14 in. radius, respectively. Polysiloxane 1 remained about the same, 0.3 in. without and 0.37 in. with T4.5 elastomer. Unfortunately, Epoxy 4 with and without T4.5 elastomer was not evaluated due to time constraints and the number of test apparatuses.

Table 10.—Cathodic disbondment resistance of the primer selection coating systems data set.

System Names	Disbondment (inches)	Notes
Epoxy 1	0.42	No blistering, epoxy easy to remove
Epoxy 1 + T4.5	0.14	No blistering, Elastomer and Duraplate hard to separate, bonded together, Duraplate easier to remove from steel, not adhered as well
Epoxy 3	2.25	Random blistering all over steel pipe (hundreds) full circumference, coating easily removed
Epoxy 3 + T4.5	0.5	No obvious blistering, the elastomer is difficult to remove from the epoxy, epoxy difficult to remove
Epoxy 4	N/A	Not tested
Epoxy 4 + T4.5	N/A	Not tested
Polysiloxane 1	0.3	One blister 0.3780 from defect, easy to chip away from steel
Polysiloxane 1 + T4.5	0.37	Strongly adhered, extremely difficult to remove
System 4	1.25	Coating easily removed when wet, some corrosion under coating
System 4 + T4.5	1.4	One massive blister 1.5535 inches from defect, small blisters on opposite side, vinyl bonded strongly to elastomer, vinyl easy to tear off steel
System 5EZ	0.75	Coating blistered around defect, otherwise vinyl well adhered to steel
System 5EZ + T4.5	0.5	No blistering, elastomer bonded strongly to vinyl, vinyl well adhered to steel

5.3.7. Slurry Erosion

Figure 15 shows the erosion resistance of the primers study and compared the results to mild steel and stainless steel. The side-by-side comparison showed T4.5 elastomer significantly improves erosion resistance compared to the primers. T4.5 elastomer had about 45 times less material loss than steel and three times less than stainless steel 304. The T4.5 elastomer result used a total of 12 replicates (two replicates per coating system) and were all combined to show the reproducibility of the results. PE 2 has been discontinued by the coating manufacturer. The polyurethane coating systems are resilient and mitigate erosion as good as stainless steel 304.

Selecting Primers for Cavitation Resistant Coating Systems

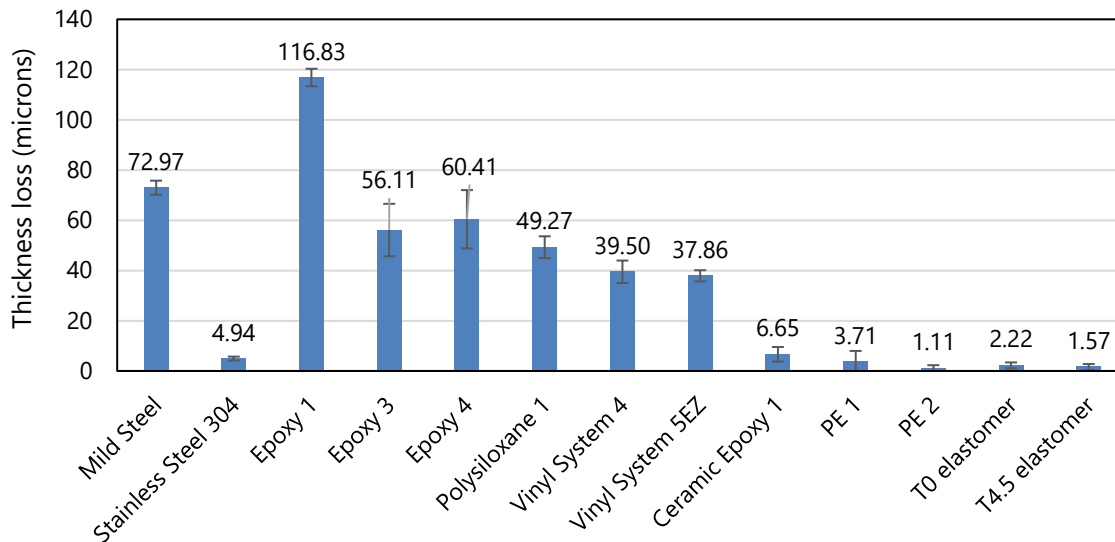


Figure 15. Erosion resistance of primer selection coating systems data set material loss in 96-hr test. The T4.5 elastomer was compiled from the six different coating systems to show the consistency of performance.

5.3.8. Cavitation

Figure 16 shows the results of the different primers using optimized T4.5 elastomer. Epoxy 1 and Polysiloxane 1 showed good cavitation resistance and the tests were terminated after 250 hrs. Vinyl System 4 peeled completely off the substrate as soon as the cavitation penetrated T4.5 elastomer as was predicted by the peel adhesion test results. Epoxy 3 had early onset damage but met the 250-hr threshold without penetrating to the substrate. Epoxy 4 failed to the substrate the quickest, similarly predicted by adhesion testing. This result shows the requirement of a complete system to have good adhesion throughout to provide cavitation/erosion resistance. Vinyl System 5EZ was not evaluated due to limited availability on the cavitation apparatus.

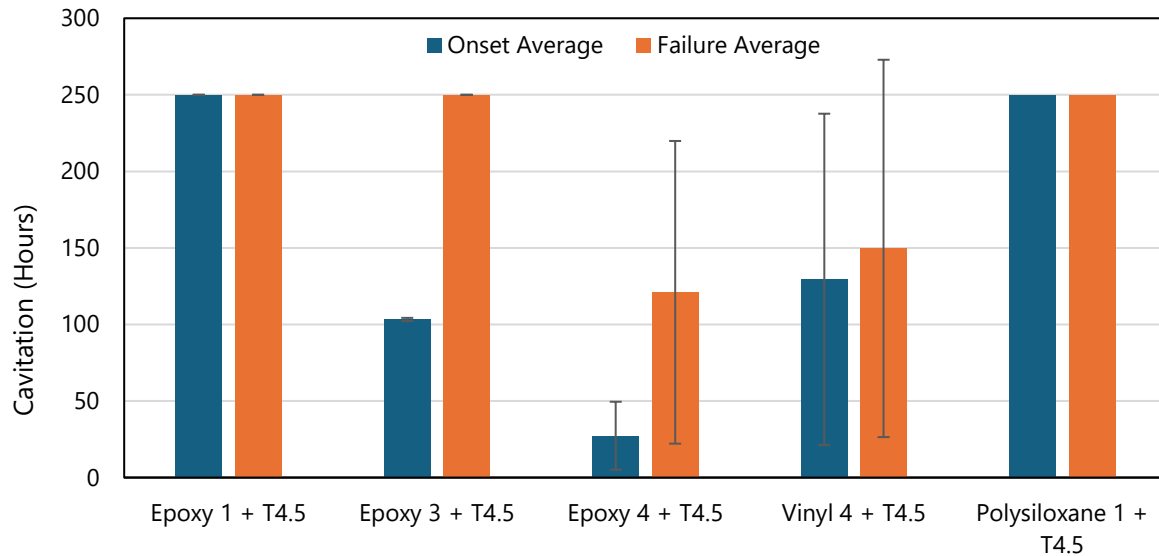


Figure 16. Cavitation resistance testing of the primer selection coating systems.

6.0 Discussion

Reclamation developed a cavitation/erosion resistant coating under S&T Project 23009. The breakthrough formulation (T0) was initially identified to have similar performance to the commercially available coatings. The research led to an optimized formulation T4.5, which outperformed the commercial products.

This project identified four primers that provided adequate wet adhesion with the optimized T4.5 elastomer formulation: Vinyl System 5EZ, Epoxy 1, Epoxy 10, and Polysiloxane 1, will potentially survive high-velocity water service up to 100 ft/s. Epoxy 10 system needs to be evaluated using the same testing protocols. Three primer systems showed good corrosion resistance for water immersion service conditions, erosion resistance, and cavitation resistance.

The corrosion protection (undercutting resistance) of primers in cyclic weathering was reduced when the T4.5 elastomer was applied on top of corrosion resistant primers, resulting in increased undercutting values. It is believed that water absorption in T4.5 elastomer causes significant swelling and internal stress during wetting and drying cycles that is transferred into the primer, accelerating corrosion along the steel interface at the scribe. This was opposite from the first study using the thermoplastic polyurethane T0, probably due to lower internal stress. The undercutting resistance for T4.5 elastomer was acceptable for water immersion, but not cyclic exposure. T4.5 cavitation/erosion resistance coating should not be used in fluctuating immersion service unless Vinyl System 5EZ is used as the primer system.

EIS showed T4.5 elastomer had larger pores resulting in mid-frequency resistive behavior compared to the primer systems without T4.5. ECM could quantify the resistive behavior in the

Selecting Primers for Cavitation Resistant Coating Systems

T4.5 elastomer. Polysiloxane 1 improved the corrosion protection (undercutting and barrier properties) compared to Epoxy 1. Both systems have two coats of Epoxy 1 and the only difference is that the high-barrier polysiloxane is an intermediate layer for Polysiloxane 1 + T4.5.

T4.5 elastomer had either no effect or slight improvement in cathodic disbondment resistance except for Vinyl System 4, which disbonded more than the primer alone. This shows that T4.5 elastomer is compatible with cathodic protection.

Laboratory data showed T4.5 elastomer provided significantly better erosion resistance than the primers. T4.5 elastomer performed better than mild steel by 45 times and stainless steel 304 by 3 times. Field trials for erosion resistance should be performed to validate in real world conditions. Possible field trials would include turbine runners or pump impellers that suffer from erosion and cavitation damage, and these facilities should be contacted for potential trials.

This project demonstrated multiple primers compatible for use with the new cavitation/ erosion resistant coating, resulting in a complete system. Reclamation specifies USACE Vinyl System 5EZ, Epoxy 1, and Polysiloxane 1 for long-term corrosion protection in water immersion service, including high velocity water service, adding the T4.5 elastomer as a topcoat could solve erosion and cavitation service conditions where these primers didn't work well. Additional field trials should be installed to validate this research using the three best corrosion resistant primers identified in this project.

6.1. Field Implications from Tasks 1 and 2

The cavitation intensity will be the limiting factor for coatings; they have been demonstrated to provide cavitation resistance in mild cavitation service such as draft tubes or outlet pipes. Questions remain about maximum cavitation intensity or unit capacity that can be sustained for each coating system. Initial implications can be drawn from the prior field observations and results for this S&T project 24005 (Final Report ST 2026-24005-01).

The previously reported results showed the commercially available cavitation resistant coatings at Nathaniel Washington Powerplant on the Unit G21 turbine runner at Grand Coulee Dam to have PE 1 damage within six weeks of operational use within the most severe cavitation zone, but no damage in lower cavitation intensity zones. PE 2 had large disbondment areas [2]. The cavitation intensity is similar or slightly higher than the laboratory cavitation test. When cavitation intensity was increased in laboratory testing, coating damage to the substrate was observed within 12 hrs [3]. This demonstrates that cavitation resistant coatings remain effective up to a specific threshold of cavitation intensity but are damaged if this intensity exceeds the damage threshold.

Field testing of Epoxy 1 + T4.5 system showed minimal damage after 21-months/ 8500 hrs of operation (1-year of continuous generation time) on a 15-megawatt turbine runner at Estes Powerplant. Given that T4.5 elastomer has shown the best laboratory performance, monitoring of this field trial should continue. The cavitation intensity at Estes Powerplant is unknown but these results indicate it is below the damage threshold for T4.5 elastomer. PE2 is also in testing at this

facility and will continue to serve as a benchmark. Additional field trials are needed to determine if the T4.5 elastomer will damage at other facilities with larger units and more intense cavitation.

Discussions with several facilities indicated a desired service life of 5-6 years, which would eliminate one full maintenance cycle. Maintenance on a 3-year rotation is currently common for many facilities. Removing a maintenance cycle would allow many facilities to generate power during the 3-6 months that otherwise would have been shut down, depending on water availability.

6.2. Next Steps

The next steps need to validate and to commercialize the Reclamation cavitation resistant coating. The R&D office will be consulted to prioritize the future work due to limited funding and budgets available. Additional partners may be required to help with this effort.

- Evaluate Epoxy 10 with and without T4.5 elastomer using the testing protocols.
- Perform field trials
 - For slurry erosion mitigation on turbine runners or pump impellers.
 - Using Epoxy 1, Polysiloxane 1, and Vinyl System 5EZ primers with T4.5 elastomer.
 - On different sized turbine runners with varying cavitation intensities for determining limitations and validation.
 - At Nathaniel Washington Powerplant unit G19-21 to directly compare PE 1 with Reclamation's coating in high cavitation intensity.
 - In draft tubes, and other lower intensity cavitation to determine service life.
- Patent coating formulations and commercialize by licensing patented technology
 - Work with commercial manufacturers to investigate pigmentation type and loading to further optimize the coating system (reinforce) or to provide color. Every change or modification requires evaluation to verify performance.
- Collaborate with other agencies
 - Department of War/ Navy to determine if the coating system will work for their needs, ships, submarines, etc.
 - USACE and TVA for their service conditions, the Ohio River's harsh conditions where Vinyl System 5EZ has a limited-service life, adding the T4.5 elastomer could mitigate the severe erosion conditions.

- Computational model cavitation intensities on Estes Powerplant turbine runners.

7.0 Conclusion

Hydropower infrastructure such as turbine runners, valves, and outlet pipes are frequently exposed to high-velocity water flows that cause cavitation damage. Traditional repair methods, including stainless-steel weld overlays, are costly, time-consuming, and often require frequent maintenance. Existing commercial coatings fail quickly under mild to moderate cavitation conditions, leading to increased downtime, reduced power generation, and higher operational costs. There is a critical need for durable, field-applicable coatings that can extend the service life of these components and reduce maintenance frequency.

The current S&T project consisted of the following three tasks. Final report ST 2026-24005-01 covers Tasks 1 and 2, and this Final report ST 2026-24005-02 covers Task 3.

1. Continuation of monitoring prior field trials of the commercially available cavitation resistant coatings on Grand Coulee G21 turbine runner.
2. Field trials of Bureau of Reclamation developed cavitation resistant coatings.
3. Laboratory corrosion protection assessment of Bureau of Reclamation developed cavitation resistant coatings.

This Final report ST-2026-24005-02 investigated compatibility between the Reclamation developed cavitation resistant coating with various commercial primers or complete coating systems to provide cavitation, erosion, and corrosion protection in high-velocity water environments. The goal of the study is to identify multiple primers or coating systems. Further, this investigation aids Reclamation in identifying potential coating manufacturers to license the technology.

Two sequential studies were performed. The baseline laboratory study investigated the original Reclamation formulation T0 and compared it to the best commercially available cavitation resistant coating systems from S&T project 20024. The baseline study showed Epoxy 1 + T0 to perform similarly to the commercial products. Peel adhesion correlated to the cavitation results; therefore, peel adhesion was used for pre-screening primers for the subsequent study. Peel adhesion using the optimized T4.5 elastomer identified four primers (Epoxy 1, Epoxy 10, Polysiloxane 1, and Vinyl System 5EZ) to advance to the corrosion protection study. However, Epoxy 10 was not identified in time to be included. Each of the three primers evaluated met the testing requirements for corrosion protection in water immersion service, cathodic disbondment resistance, erosion resistance, and cavitation resistance.

This project demonstrated multiple primers for use in a complete system. While Reclamation currently specifies Epoxy 1, Polysiloxane 1, and Vinyl System 5EZ for long-term corrosion protection in water immersion service, adding the T4.5 elastomer as a topcoat could solve erosion and cavitation service conditions where these primers are damaged.

Implementing the developed cavitation resistant coating into field use requires additional understanding of the cavitation intensity and unit capacity limits for these coatings. The ongoing field trials at Nathaniel Washington Powerplant on the Unit G21 turbine runner at Grand Coulee Dam and Estes Powerplant Unit 2 turbine runner will continue to provide valuable long-term testing data. Current findings show the coatings are effective up to an unknown threshold of cavitation intensity.

This laboratory study confirmed that future field trials should use Epoxy 1, Polysiloxane 1, and Vinyl System 5EZ primers with T4.5 elastomer. Additional field trials should be installed selecting facilities for cavitation intensity and unit capacity. In addition, full-scale runner applications in erosion environments should also be investigated.

8.0 References

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9.0 Appendix A – Coatings Rating Criteria

Immersion Testing (Dilute Harrison, Deionized):

Excellent: No visual defects

Good: No blistering, minor rust creep up to 1/8 in.

Fair: No blistering, moderate rust creep up to 1/4 in.

Poor: Blistering, delamination or rust creep over 1/4 in.

Cyclic Weathering Testing (BOR, Prohesion, FOG):

Excellent: No blistering, minor rust creep up to 1/8 in.

Good: No blistering, minor-moderate rust creep up to 1/4 in.

Fair: No blistering, moderate rust creep up to 1/2 in.

Poor: Blistering, delamination or rust creep > 1/2 in.

Accelerated Weathering (QUV)

Excellent: No visual defects

Good: No blistering, no rust creep, minor color change

Fair: No blistering, moderate color/gloss change, chalking, or undercut up to 1/8 in.

Poor: Any of the following: blistering, delamination, rust creep > 1/8 in.

EIS (immersion):

Excellent: After 5000 hrs - Minimal degradation < 1 order of magnitude @ 0.01 Hz and > 10⁹ ohms

Good: Minimal degradation after 5000 hrs =< 2 orders of magnitude @ 0.01 Hz and >= 10⁸

ohms Fair: Moderate degradation after 5000 hrs =< 3 orders of magnitude @ 0.01 Hz and >= 10⁷ ohms

Poor: Signification degradation after 5000 hrs > 3 orders of magnitude @ 0.01 Hz

Pull off Adhesion (initial, dry):

Excellent: >= 2,500 psi

Good: >= 1,500 psi

Fair: >= 1,000 psi

Poor: < 1,000 psi

Pull off Adhesion (Wet):

Excellent: >= 2,000 psi

Good: >= 1,000 psi

Fair: >= 500 psi

Poor: < 500 psi

Peel Adhesion (Dry or wet)

Excellent: = 30 + pli Elastomer stretches and breaks

Good: = 25-30 pli Elastomer stretches and breaks, with minor propagation

Fair: = 20-25 pli Elastomer stretches and breaks, with minor propagation

Poor: < 19 pli Elastomer propagates and disbonds

Erosion (USBR-5071-2015):

Excellent: < 3 mg/hr average loss/ < 5 microns per 96 hr

Good: 3-10 mg/hr average loss/ 5-30 microns per 96 hr

Fair: 11-50 mg/hr average loss/ 30-60 microns per 96 hr

Poor: 50-100 mg/hr average loss/ 60+ microns per 96 hr

Impact:

Excellent: ≥ 160 in-lbs

Good: ≥ 100 in-lbs

Fair: ≥ 50 in-lbs

Poor: < 50 in-lbs

Cathodic Disbondment (ASTM G8)

Excellent: Disbondment radius < 0.25 in.

Good: Disbondment radius < 0.5 in.

Fair: Disbondment radius < 1 in.

Poor: Disbondment radius > 1 in.

Knife Adhesion Testing (ASTM D6677)

Excellent: ASTM Rating 8-10 - Coatings is extremely difficult to remove. Chips up to 0.8 mm by 0.8 mm = 10, Chips up to 3.2 mm by 3.2 mm = 8,.

Good: ASTM Rating 5-7 - Coating is difficult or at least somewhat difficult to remove. Chips up to 6.3 mm by 6.3 mm = 6.

Fair: ASTM Rating 3-4 - Coating chips in excess of 6.3 mm by 6.3 mm, can be remove with light pressure from a knife blade.

Poor: ASTM Rating 0-2 - Coating peels with fingers once started with a knife blade.

Cavitation (USBR)

Excellent: onset damage 200 + hrs, damage to substrate 250+ hrs

Good: onset damage 75-150 hrs, damage to substrate 100-250 hrs

Fair: onset damage 24-75 hrs, damage to substrate 50-100 hrs

Poor: onset damage less than 24 hrs, damage to substrate 50 hrs

10.0 Appendix B – Erosion Testing Procedure

RECLAMATION

Managing Water in the West

Test Procedure USBR-5071-2015

Standard Test Method for Erosion of Coatings by Flowing Water Slurry

**Materials and Corrosion Laboratory
Technical Service Center
Denver, CO**

Mission Statements

The mission of the Department of the Interior is to protect and manage the Nation's natural resources and cultural heritage; provide scientific and other information about those resources; and honor its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

BUREAU OF RECLAMATION
Technical Service Center, Denver, Colorado
Test Procedure USBR-5071-2015

Test Method for Erosion of Coatings by Flowing Water Slurry

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10.1. Abstract

Reclamation's Materials and Corrosion Laboratory (MCL) has developed a new test protocol to evaluate coatings which are subjected to slurry erosion damage in sediment-laden immersion exposure. This test has initially been utilized as a screening/ranking method in selection of coatings for the aforementioned severe service environments. This is a harsh service environment which is not currently replicated by a standardized test method. Such a test may be useful for other organizations in the water and wastewater industries. It is expected that this standard will be useful in selection of coatings intended for raw water immersion service particularly in situations where there are entrained solid particulates present in flowing water.

The goal is to accurately evaluate coating systems to determine which provides the longest possible service life. Weight loss is measured during extended testing in order to evaluate and compare coating wear rates over time. The slurry erosion test has been developed and refined to enhance reproducibility and improve usability. The ASTM standards committee D01.48 is currently considering the proposed test method for approval.

10.2. Introduction

The United States Bureau of Reclamation (Reclamation) Materials and Corrosion Laboratory (MCL) conducts performance testing of a variety of coatings for use on Reclamation equipment and infrastructure. As a test lab, MCL utilizes ASTM standards in our materials testing procedures as well as our construction specifications.

It is standard practice for MCL to test coatings for corrosion protection, resistance to weathering, and cathodic disbondment using ASTM D870, ASTM D2794, ASTM D5894, ASTM D4587, and ASTM G8 (1-5). While these tests are necessary to verify acceptable corrosion performance, they do not forecast performance for coatings exposed to water with high sediment loads. ASTM D4060 (6) evaluates the abrasion resistance of a coating but does not simulate the slurry erosion experienced on hydraulic equipment. To address this issue, MCL developed a slurry erosion test protocol. The goal was to adapt the test to an ASTM standard for other laboratories to utilize. Potential beneficiaries include coatings manufacturers, other water municipal water management agencies such as Metropolitan Water District in Southern California, Denver Water, etc., and also raw water providers (irrigation districts) and wastewater treatment providers. Examples of affected equipment include pump casings, impellers, and turbines. Higher velocity piping with bends or elbows, trashracks and gratings could also be impacted. As another example, agencies such as the United States Army Corps of Engineers could benefit by reducing coating damage from swirling debris on large tainter gates.

Facility owners are interested in utilizing coatings which provide the lowest life cycle costs in harsh environments. Outages (especially unscheduled) are costly and inconvenient. Premature coating failures in pump casings at the Durango Pumping Plant (Photo 1) prompted a search for a more durable coating. These failures were a direct result of the scouring caused by the presence

of sediment in the Animas River during typical springtime runoff. Municipal water and sewer system customers are indirectly affected by operation of the infrastructure because maintenance costs and capital expenditures are passed along. Therefore, the general public also has a stake in the development, selection, and proper utilization of long lasting and high performance protective coatings.

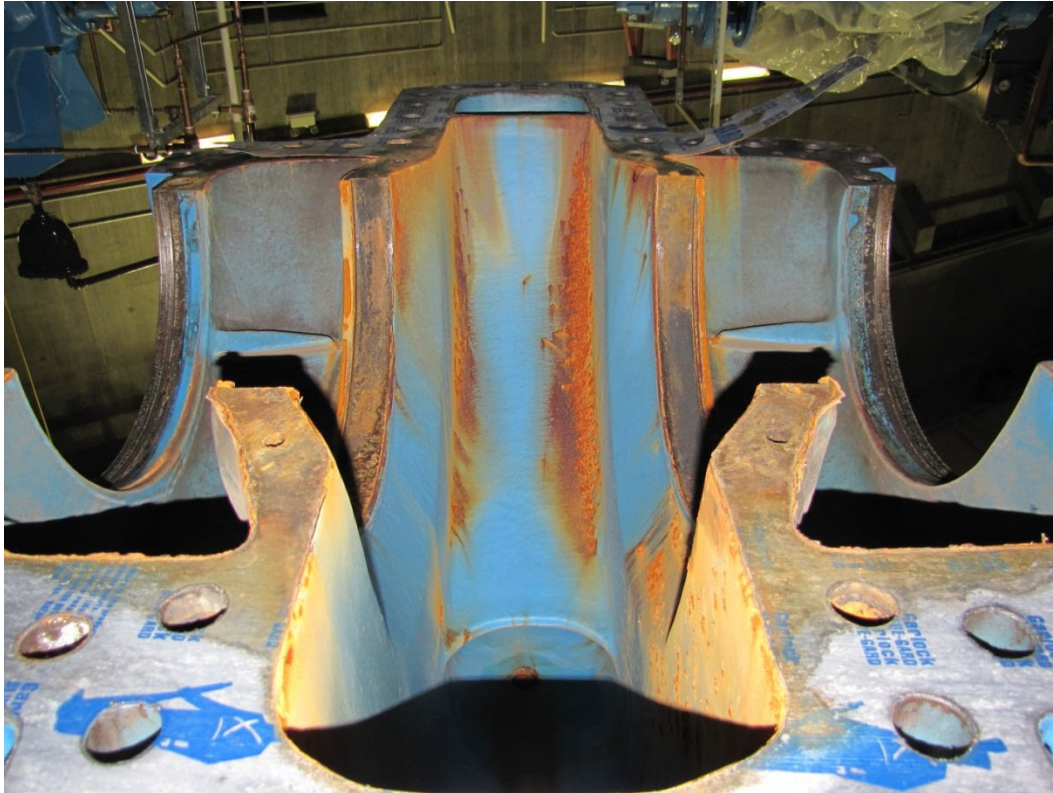


Photo 1 Erosion damage to the pump volute at Durango Pumping Plant (Winter 2011)

Coating manufacturers and end users will utilize the test standard. Manufacturers can use the standard for developing new erosion / abrasion resistant coatings. End users can evaluate multiple products and optimize their protective coatings maintenance program for equipment subject to immersion in flowing water with high sediment loading.

10.3. Standard Test Method for Erosion of Coatings by Flowing Water Slurry

1. Scope

1.1 This test method provides a procedure for evaluating the erosion of polymeric materials, namely coatings, in vigorously agitated water slurry. This procedure simulates the degradation caused by sand, silt, and other suspended sediments in raw (or untreated) water.

Note 1—The scrub resistance of paints can be evaluated by ASTM D4213 and ASTM D2486. For the abrasion resistance of concrete materials, ASTM C1138 should be used. ASTM G32 and ASTM G134 should be used for cavitation erosion of a solid, and ASTM G73 provides a general method for liquid impingement of a solid.

1.2 This test method is intended to carry out and isolate the erosion of polymeric materials, whether they are coatings, polymer composites, or otherwise. The polymer degradation results from a preferential erosion of the softer polymer matrix upon impingement of the harder sediments suspended in the water. Over time, the repeated mechanical defects result in large-scale erosion of the polymer matrix.

Note 2—Polymeric coatings often contain hard particulate matter such as ceramic, glass, or metal pigments as fillers and can be considered a composite with the softer polymer serving as the matrix. These coatings can be tested by this method; however, the size and shape of the fillers will have a significant effect on the erosion processes.

1.3 The erosion of a coating can be classified by several phases or periods. This is known as the cumulative erosion-time curve. First, an incubation period may be observed as the erodant impacts the polymer surface with little or no damage. This is most pronounced for elastomeric coatings which absorb the erodant's energy with high efficiency. The acceleration period begins as the erosion rate begins to increase. This signifies the loss of the outermost polymer layers. A maximum rate period follows, marked by a high, constant erosion rate. In some cases, this is followed by a deceleration of the rate and a subsequent lower constant erosion rate. This is defined as the terminal period.

Note 3—ASTM G73 provides a detailed description of cumulative erosion-time curves.

1.4 The values stated in acceptable metric units are to be regarded as the standard.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 ASTM Standards:

C1138 Test Method for Abrasion Resistance of Concrete (Underwater Method)

D2486 Test Method for Scrub Resistance of Wall Paints

D4213 Test Method for Scrub Resistance of Paints by Abrasion Weight Loss

G32 Test Method for Cavitation Erosion Using Vibratory Apparatus

G40 Terminology Relating to Wear and Erosion
G73 Test Method for Liquid Impingement Erosion Using Rotating Apparatus
G134 Test Method for Erosion of Solid Materials by a Cavitating Liquid Jet

3. Terminology

3.1 *Definitions*—Definitions for terms relevant to this test method have been reproduced from Terminology G40. In some cases the definitions have been simplified to describe the application intended in this test method. For additional terms related to wear and erosion, see Terminology G40.

3.1.1 *Acceleration period, n*—the stage following the incubation period during which the erosion rate increases from near zero to a maximum value.

3.1.2 *Carrier fluid, n*—fluid that transports impinging solid particles and that gives the particles their momentum relative to the solid surface in which they are impinging.

3.1.3 *Cumulative erosion, n*—the total amount of material lost from a solid surface during all exposure periods since it was first exposed to impingement as a newly-finished surface.

3.1.4 *Cumulative erosion-time curve, n*—a plot of cumulative erosion versus cumulative exposure duration, usually determined by periodic interruption of the test and weighing of the specimen. This is the primary record of an erosion test. Most other characteristics, such as the incubation period, maximum erosion rate, terminal erosion rate, and erosion rate-time curve, are derived from it.

3.1.5 *Damage, n*—any effect on a solid body resulting from its exposure, including loss of material, surface deformation, or any other changes in microstructure, properties, or appearance.

3.1.6 *Deceleration period, n*—the stage following the acceleration period or maximum rate period during which the erosion rate has an overall decreasing trend although fluctuations may be superimposed on it.

3.1.7 *Erodant, n*—a material that is producing, or has produced, erosive wear.

3.1.8 *Erosion, n*—progressive loss of original material from a solid surface due to mechanical interaction between that surface and impinging solid particles.

3.1.9 *Erosion rate, n*—any determination of the rate of loss of material (erosion) with exposure duration.

3.1.10 *Erosion rate-time pattern, n*—any qualitative description of the shape of the erosion rate-time curve in terms of the several stages of which it may be composed.

3.1.11 *Incubation period, n*—the initial stage of the erosion rate-time pattern during which the erosion rate is zero or negligible compared to later stages. Also, the exposure duration associated with this stage.

3.1.12 *Maximum rate period, n*—a stage following the acceleration period, during which the erosion rate remains constant (or nearly so) at its maximum value.

3.1.13 *Particle concentration, n*—a measure of the solid particle content in a mixture of particles and fluid.

3.1.14 *Slurry, n*—a suspension of solid material in a liquid.

3.1.15 *Terminal period, n* —a stage following the deceleration period, during which the erosion rate has leveled off and remains approximately constant (sometimes with superimposed fluctuations) at a value substantially lower than the maximum rate attained earlier. This occurs in some, but not all tests.

4. Significance and Use

4.1 This test method is intended to measure the degradation of a polymeric coating by simulating the “erosion” caused by the constant wash of “slurry” over a surface. The slurry consists of a defined “erodant” and a “carrier fluid,” namely water. The test results are the most significant when the slurry is designed in accordance with the anticipated exposure environment, including the proper “particle concentration” for the slurry. Although the test method is designed to examine the erosion resistance of a coating to slurries, plastic films, ceramics, and metals may or may not also be evaluated by this method.

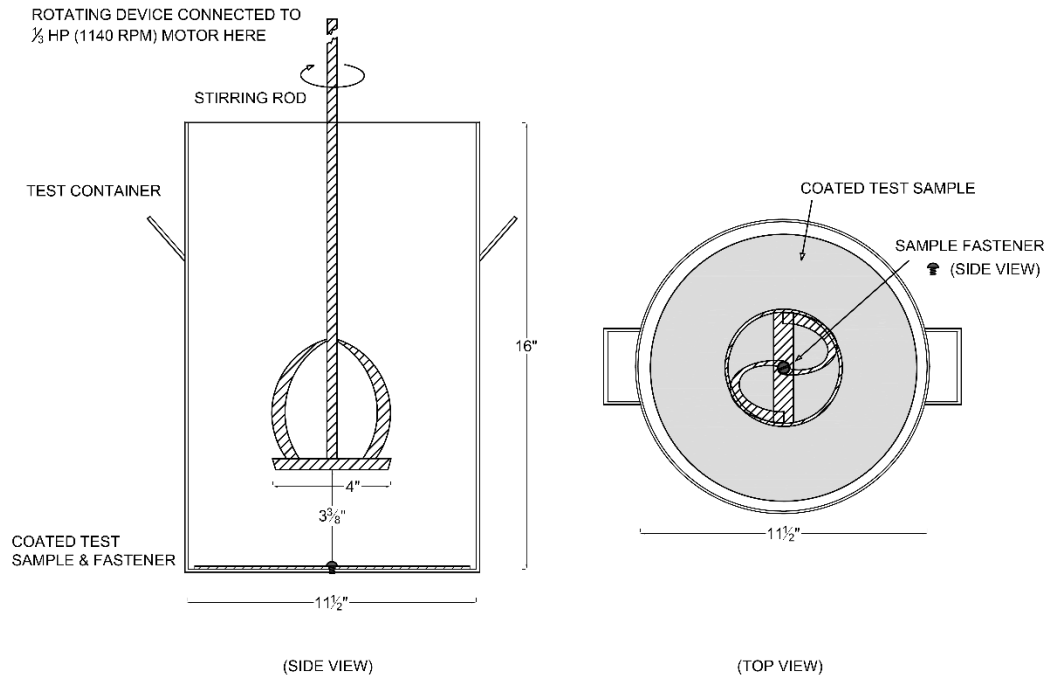
4.2 The “damage” resulting from the slurry exposure is recorded by means of the mass loss or the “cumulative erosion” of a coating per exposure period.

4.3 The results can be used to rank a set of coating systems evaluated by this method. An “erosion rate-time pattern” will evolve following a suitable testing procedure. The critical elements of this curve should be identified for best results. The “incubation period” or “acceleration period” may be a key variable for certain applications; for others, the “maximum rate period” may be most important. It is recommended to use the “terminal period” when determining the long-term erosion resistance of a coating. When extrapolated for estimated coating service life, this “erosion rate” typically provides the best correlation to the actual service results.

4.4 The method is most applicable for testing of materials which will be exposed to flowing, raw water conditions since solid materials are typically suspended in this medium. Examples of where this will occur include pump casing coatings, pipe linings, or canal linings. The actual erosion resistance of a coating is a function of the material’s properties and an empirical correlation between these has yet to be obtained. It is important to note that the complexity of this relationship is increased with the addition of pigments or fillers to a coating system, for which size, shape, and material are all key factors.

5. Apparatus

5.1 *Test container*—An 11-1/2-in (inch) inside diameter and 16-in tall cylindrical tank shall be used to hold the slurry and test samples (see Fig. 1)



Drawing 1. Erosion test configuration

5.2 Rotating device—A vertically oriented 1/3 horsepower, 1,140 rpm AC motor connected to a helical paint stirring rod or similar device shall be used. The clearance between the rod and tank bottom is defined as $3\text{--}3/8 \pm 1/8$ in.

5.3 Suspended particles—16-grit brown aluminum oxide angular abrasive is charged at 1.0 kg per 16 L of tap water shall be used as the erodant for this test method.

5.4 Coated Test sample—Two disks, 11-in diameter, 1/10-in thick with a 1/4-in hole in the center is coated on both sides with the material to be evaluated. Substrate material: carbon steel or aluminum alloy 5052-H32 (or equivalent yield strength).

5.5 Sample Fastener—Sample is held in place with a single screw threaded into a hole in the center of the tank.

Note 4—The apparatus for this test method is based on ASTM C1138, an abrasion resistance test for concrete that involves circulating steel ball bearings in water, with modification for slurry erosion of coatings on an aluminum or steel disk.

6. Hazards

6.1 Keep all loose clothing and materials free of the rotating stirring rod when in operation.

7. Test Specimens

7.1 Prepare the test specimens by allowing freshly applied coatings to cure completely and reach equilibrium with the surrounding air. Equilibrium is deemed when weight has stabilized over a 24-hr period. The coating film should be defect-free and tightly adhered to the substrate. Discard samples which have poor film formation or obvious defects.

7.2 A separate control test specimen should be submerged in water using a sealed container to prevent evaporation at the beginning of the test.

Note 5—If samples are freshly coated, allow two weeks for them to cure completely.

8. Standard Ranking Method

8.1 For the standard ranking method, the test period is held constant at 24 hrs. The test is run for a cumulative duration of 96 hrs or until the weight loss rate stabilizes establishing a terminal wear rate. This method should be used only when the “incubation period” and “acceleration period” are of no significance. An approximate erosion rate is then calculated using the equations provided in Section 11 and reported as detailed in Section 12.

9. Full Characterization Method

9.1 This is the recommended method when full erosion behavior characteristics such as “incubation period” and “acceleration period” are of interest.

9.2 The period must be short enough to observe the incubation period and acceleration period in the cumulative erosion-time curve. The recommended initial test period is 1-2 hrs. Increase to 24 hrs once the initial cumulative erosion-time curve characteristics have been observed.

Note 6—Some trial and error may be required to obtain a good cumulative-erosion time curve since some coatings have very high erosion resistance while others are very low.

10. Procedure

10.1 Coatings must be dry before and after slurry testing to accurately determine mass loss as a result of erosion. Dry test and control samples in an oven while maintaining temperature at 50 °C for at least 24 hrs prior to weighing. Weigh the test sample and control sample using a balance with minimal precision of ± 0.01 gram. Record this value as the initial sample weight, W_i .

10.2 Fasten the coating sample to the base of the 11-1/2-in cylindrical tank. The surface to be tested should be facing up and oriented normal to stirring rod shaft. Charge the tank with 1.0 kg of aluminum oxide abrasive and 16 L of water. Immerse the control sample in a separate control tank simultaneously.

10.3 Mount the helical paint stirring rod so that it is positioned with $3\text{-}3/8 \pm 1/8$ in of clearance from the tank bottom.

10.4 Seal the tank and agitate the slurry at 1,140 rpm in the clockwise direction for a specified period of time.

Note 7—The specified testing period for the standard ranking method is 24 hrs.

Note 8—The procedure can be interrupted overnight with no change to the significance of the test results. The samples should remain in the slurry to maintain water saturation.

10.5 Stop the rotating device. Remove the sample from the test container and rinse with water. The test and control samples should be dried at 50 °C for 24 hrs. The weight of each sample is then measured and recorded.

10.6 Repeat Steps 10.2-10.5 until the terminal wear rate has been clearly defined. This may be marked by a stabilizing in the observed erosion rate.

10.7 Repeat Steps 10.1-10.6 testing side A of disc 1 and side A of disc 2 with the non-test disc as the control sample. Calculate the terminal erosion rate. If more than 10% difference exists between samples, test side B of disc 1 and report the average and standard deviation between all three tests.

11. Calculation of Erosion Resistance

11.1 Calculate the cumulative erosion at the end of each time increment of testing as follows:

$$W_{lost,i} = (W_i - W_{i+1})_{sample} - (W_i - W_{i+1})_{control} \quad (2)$$

where:

$W_{lost,i}$ = weight loss of coating sample during test period i
 W_i = weight of coating sample prior to test period i
 W_{i+1} = weight of coating sample at the end of test period i

11.2 Calculate the erosion rate of any testing period as follows:

$$R_{erosion,i} = \frac{W_{lost,i}}{T_i} \quad (3)$$

where:

$R_{erosion,i}$ = the rate of erosion during test period i
 T_i = test duration for test period i

Note 9—The terminal wear period is the total duration of testing over which weight loss has been stable. This terminal wear period shall exclude the initial 24 hrs of testing.

12. Report

12.1 The report shall include the following:

12.1.1 Identification and properties of each test material.

12.1.2 Total cumulative time of exposure.

12.1.3 Total cumulative mass loss (mg).

12.1.4 Calculated total cumulative volume loss using the as-cured density of the material.

12.1.5 Erosion rate by mass and volume for terminal period.

12.1.6 A plot of time versus mass loss of individual test specimens and the average of all specimens of a type that were tested.

12.1.7 Any deviations from the standard test specimens, procedure, etc.

13. Precision and Bias

13.1 Precision:

13.1.1 No formal inter-laboratory test has yet been conducted; thus no information can be given on reproducibility.

13.2 Bias:

13.2.1 No statement can be made regarding the bias of this test method because there is no absolute definition or independent measurement of erosion resistance. Erosion test methods measure only relative results between different materials, and these can differ according to the method or test conditions employed.

14. Keywords

14.1 Slurry erosion; coatings; erosion resistance

11.0 Appendix C – Cavitation Testing Procedure

11.1. Reclamation Cavitation Test Method, and Analysis

11.1.1. Materials

Test samples are 4 inches by 6 inches by $\frac{3}{4}$ inches thick mild steel coupons. Coupons are prepared by solvent cleaning to SSPC-SP1, followed by abrasive blast cleaned to SSPC-SP5 white metal using LG 25 steel grit to generate a 3.5 mil minimum surface profile. Coupons will be shipped to manufacturer for application. Manufacturer will ship the samples back to Bureau of Reclamation for testing. Alternatively, the materials can be shipped to Bureau of Reclamation and applied by Reclamation staff.

All samples will be preconditioned for 2 weeks in water immersion prior to testing to ensure full water saturation prior to testing. Testing will be done in triplicate.

11.1.2. Submerged Jet Test Method

The submerged jet testing apparatus consists of a 10 horsepower (hp) pump (H₂O Power Equipment: Baldor Reliance Super E Motor and Landa Pump High pressure Model LT5030), hoses, a submerged jet, zero-degree 0.0065-inch diameter nozzles, sample holder, and a 120-gallon water tank with a clear viewing window. Samples are installed on the sample holder at a 30-degree angle from the nozzle [1, 2]. The angle allows the cavitation cloud to flow down the sample, as shown in Figure 1. Two different zones exist: an impact zone containing the jet impact along with cavitation on the sample and a pure cavitation zone, where the cavitation bubbles travel down the sample. The nozzle is placed at a 2.5-inch standoff distance from the sample. Cavitation intensity can be adjusted using a valve to increase the upstream pressure and water flow rate of the pump. The pressure and flow rates are monitored by flow meters (Endress and Hauser Picomag Bluetooth IO Link), pressure transducers (Omega model PX309-5KG5V), and Daisylab software. Testing parameters are set to 3.5 gallons per minute (gpm) flow rate, 2.5-inch stand-off, and 1450 ± 25 psi. Nozzle calibration is performed prior to testing. Atmospheric pressure and water temperatures are recorded during each test, on a daily basis.

Researchers employed a new submerged jet test procedure to expose test specimens to intense cavitation, following suggestions in the Reclamation report HL-2017-10 [2] (https://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/HL/HL-2017-10.pdf). This method tests material durability by exposing the material to an intense hydrodynamic environment that more rapidly produces cavitation and erosion damage compared to traditional venturi test methods. The submerged jet method induces cavitation using a submerged jet, similar to the ASTM G134 standard. However, the specimen is placed at a 30-degree angle to the jet, as shown in Figure 1, to minimize other physical mechanisms that may cause damage and/or wear to the surface of the sample (e.g. erosive hydrodynamic impact and shear forces).

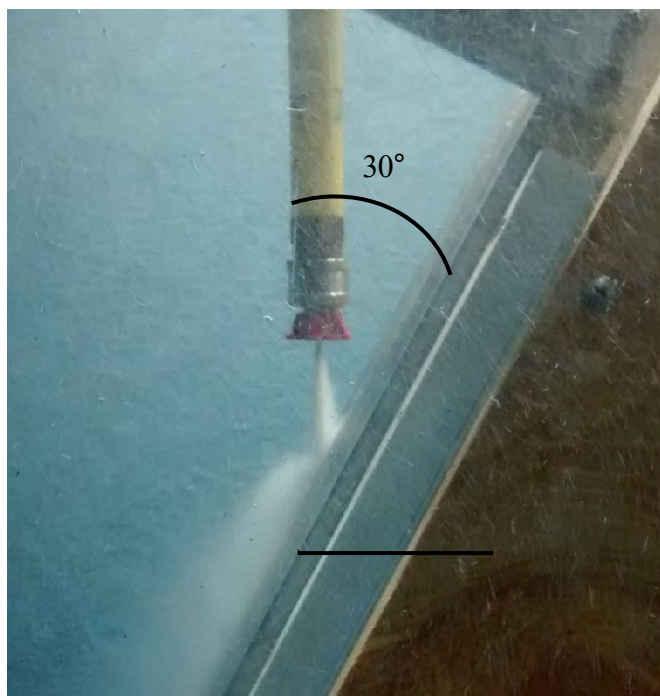


Figure C- 1. Test specimen exposed to cavitation from a submerged jet.

The test set-up is arranged so that two specimens could be tested simultaneously as shown in Figure 2. The test procedure is optimized so that the chosen flows and pressures create light frosting damage to stainless steel 316L and moderate pitting to mild steel, shown in Figure 3. Figure 4 shows minimal pitting to 308/309 stainless steel weld overlay in a 40-hr period of exposure. The testing parameters (listed above) were set to show cavitation damage on mild steel in 16 hrs and measurable damage in 40 hrs of testing, shown in Figure 5.

Samples are tested at eight hrs each day and then checked for damage periodically throughout the day. If failure to the substrate occurs, the sample is removed from testing. Samples that do not fail are returned to testing for up to a total of 40 hrs before the test is terminated. All samples that pass 40 hrs of testing are considered candidates for further testing rubrics or field trial options.



Figure C- 2. Top view (left) and side view (right) of submerged jet test set-up.

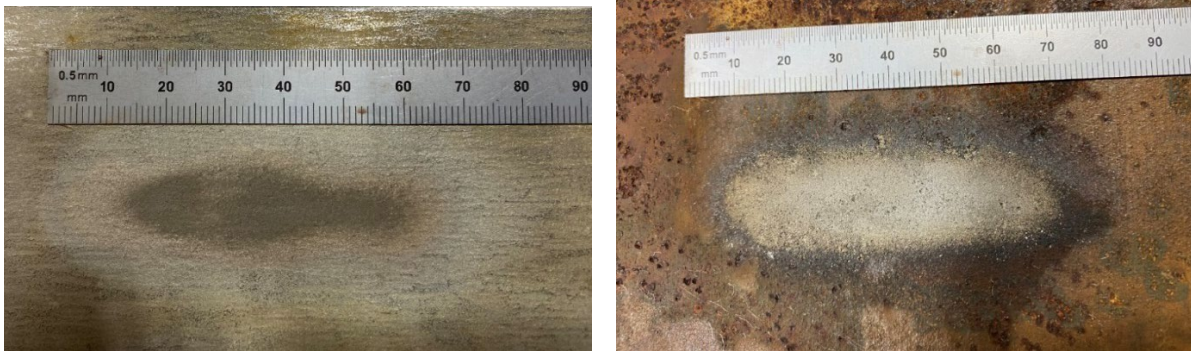


Figure C- 3. Stainless steel 316L (left) and mild steel (right) after 40 hrs exposure to submerged jet cavitation apparatus. Notice pitting caused by cavitation in the mild steel.

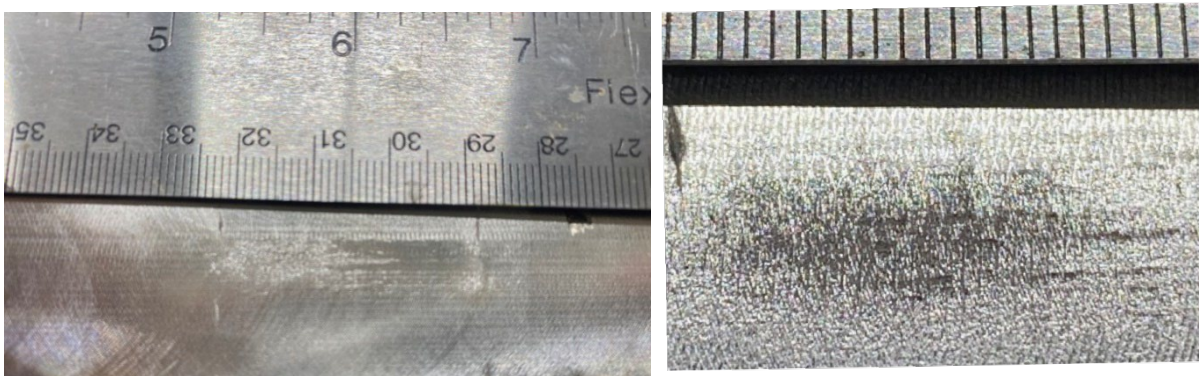


Figure C- 4. Photo of 308/309 stainless steel weld overlay after 40 hrs exposure to cavitating jet apparatus. The damaged area is significantly less than mild steel.

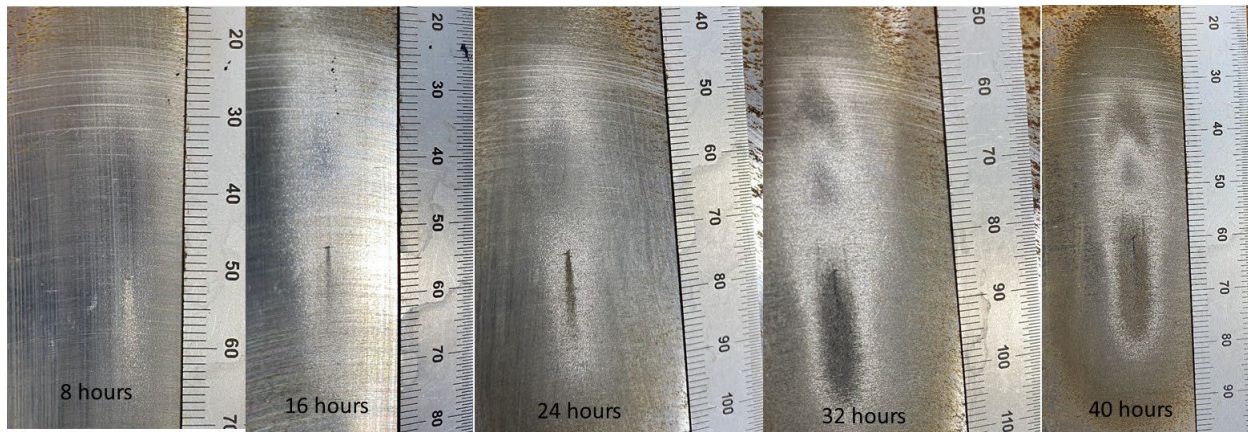


Figure C- 5. Baseline testing of mild steel and progression of cavitation damage.

11.1.3. Analysis

Weight loss is the traditional method for cavitation ASTM G132 test methods of metals, but is an impractical measurement for coatings. A coating mass loss is insignificant compared to the weight of the base substrate, and there are no balances sensitive enough to detect the small change in weight. Time to failure to substrate is used to compare coated samples.

Samples expected to pass the 40-hr test may be tested for long-term durability up to 200 hrs. For detailed analysis, a 3D Faro laser scanner will be used to monitor material loss over time. Figures 6 and 7 show a cavitated sample and the Faro laser scanned that is produced for analysis. Figures 8 and 9 show the analytical capabilities of the Faro laser on cavitated samples.



Figure C- 6. Photo of mild steel after 40-hrs of cavitation testing.



Figure C- 7. Image of material loss scanned by a 3D Faro Laser

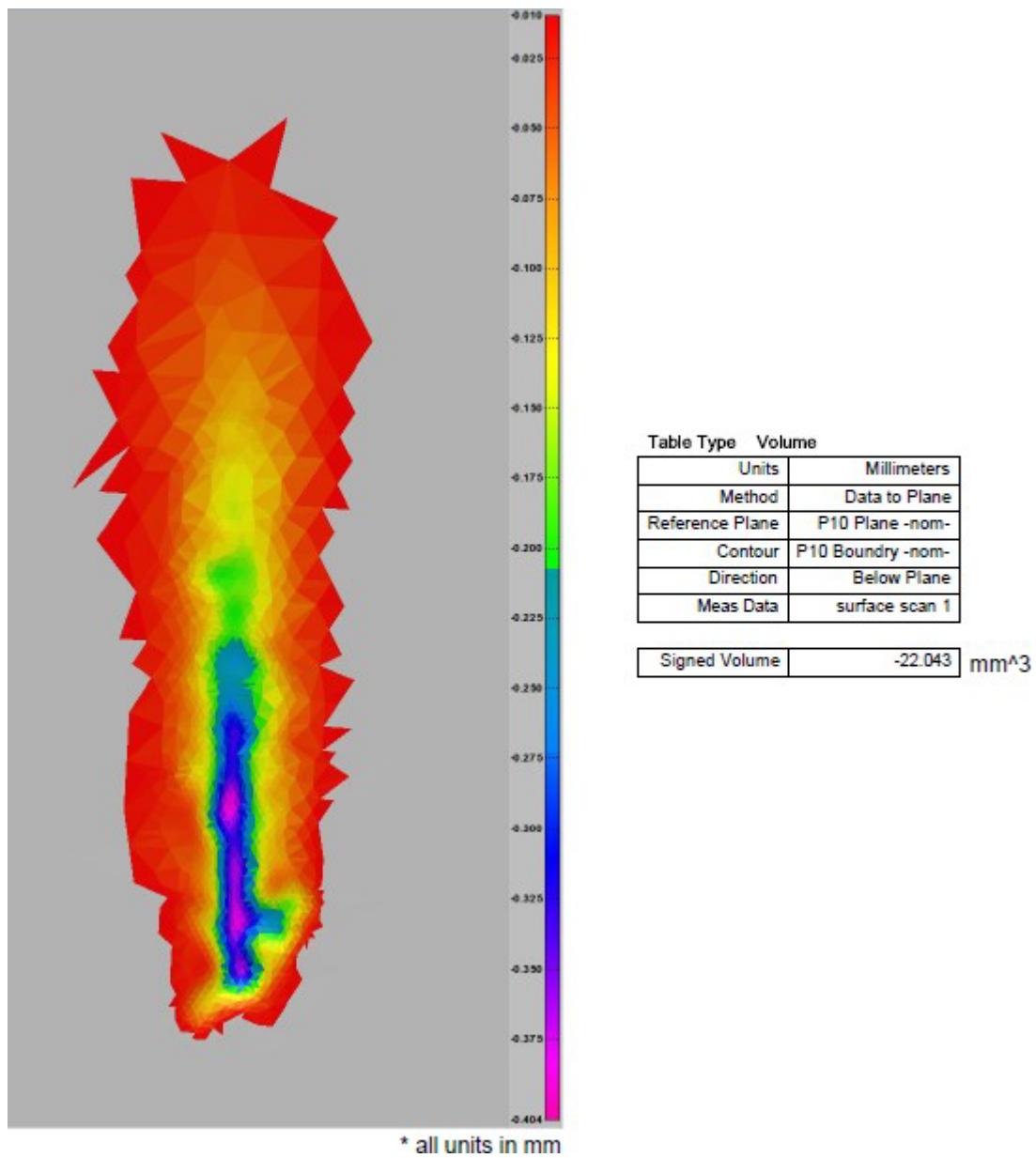


Figure C- 8. Analysis of the damage caused by the old nozzle acquired by the 3D Faro laser

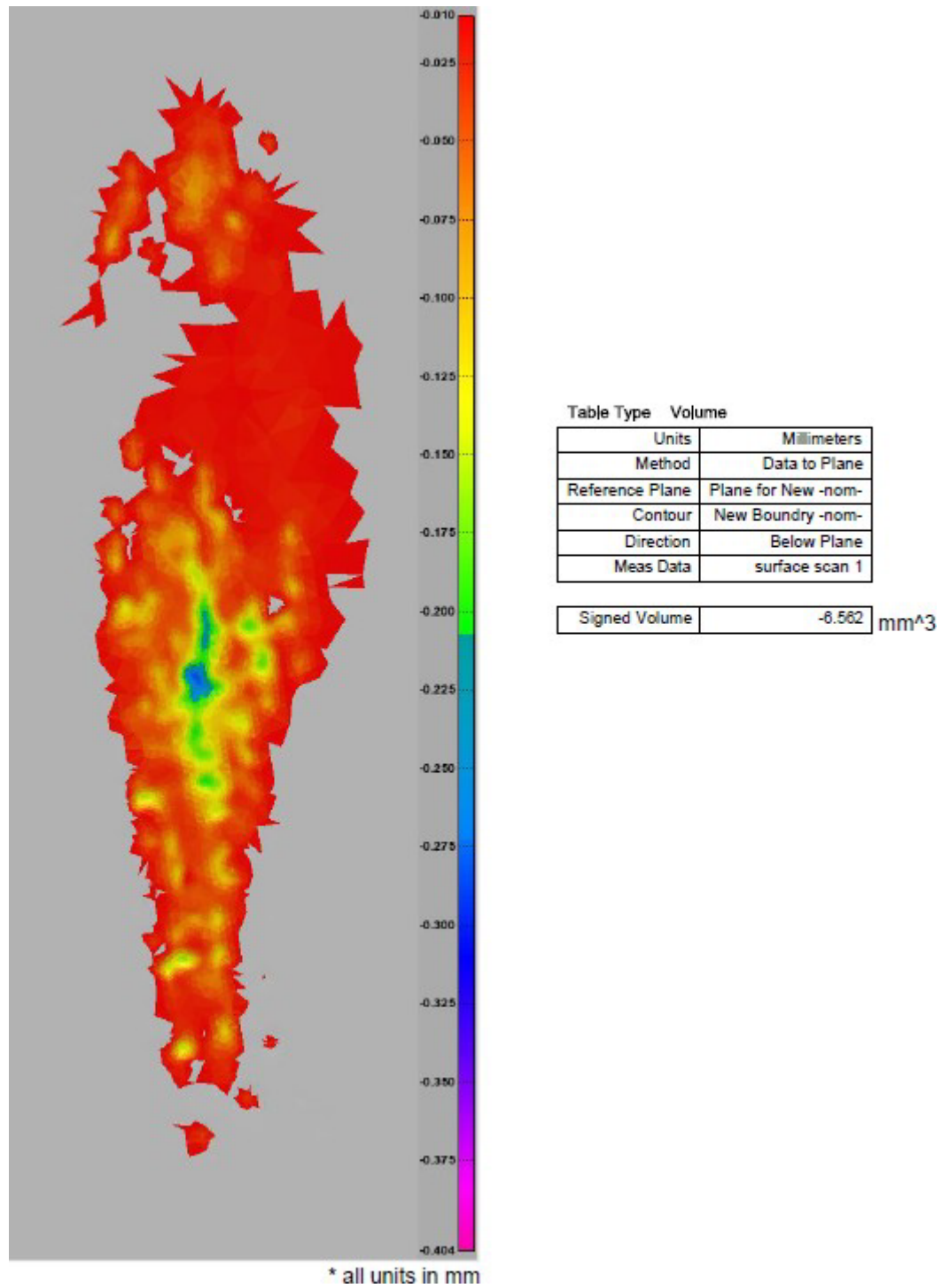


Figure C- 9. Analysis of the damage caused by the new nozzle acquired by the 3D Faro laser

11.2. References

- [1] Henderson, C., Mortensen, J., Skaja, A. "Evaluation of Field Repairable Materials and Techniques for Cavitation Damage," Bureau of Reclamation report ST-2019-8452-01, 2019.
- [2] J. Mortensen, "Cavitation detection- Method development to detect damaging cavitation," Bureau of Reclamation. Hydraulics Investigations and Laboratory Services Group. Report HL- 2017-10, Denver, CO, 2017.

12.0 Appendix D - Electrochemical Impedance Spectroscopy of Vinyl System 4, Epoxy 3, and Epoxy 4

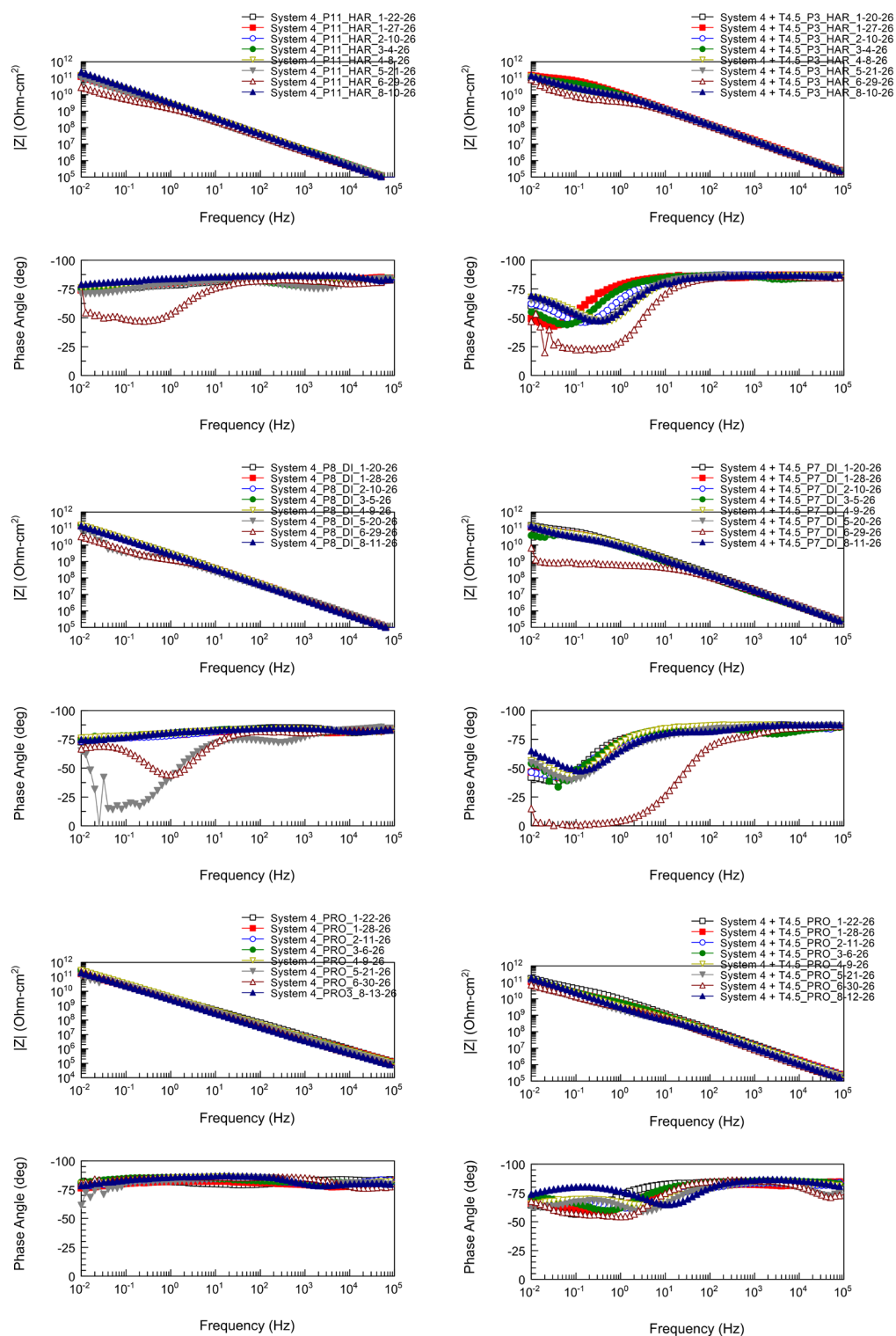


Figure D- 1. EIS of Vinyl System 4 a) in HAR without and b) with T4.5 elastomer, c) in DI without and d) with T4.5, and e) in PRO with and f) without T4.5; DI without. 6-29-26 flagged as errant data.

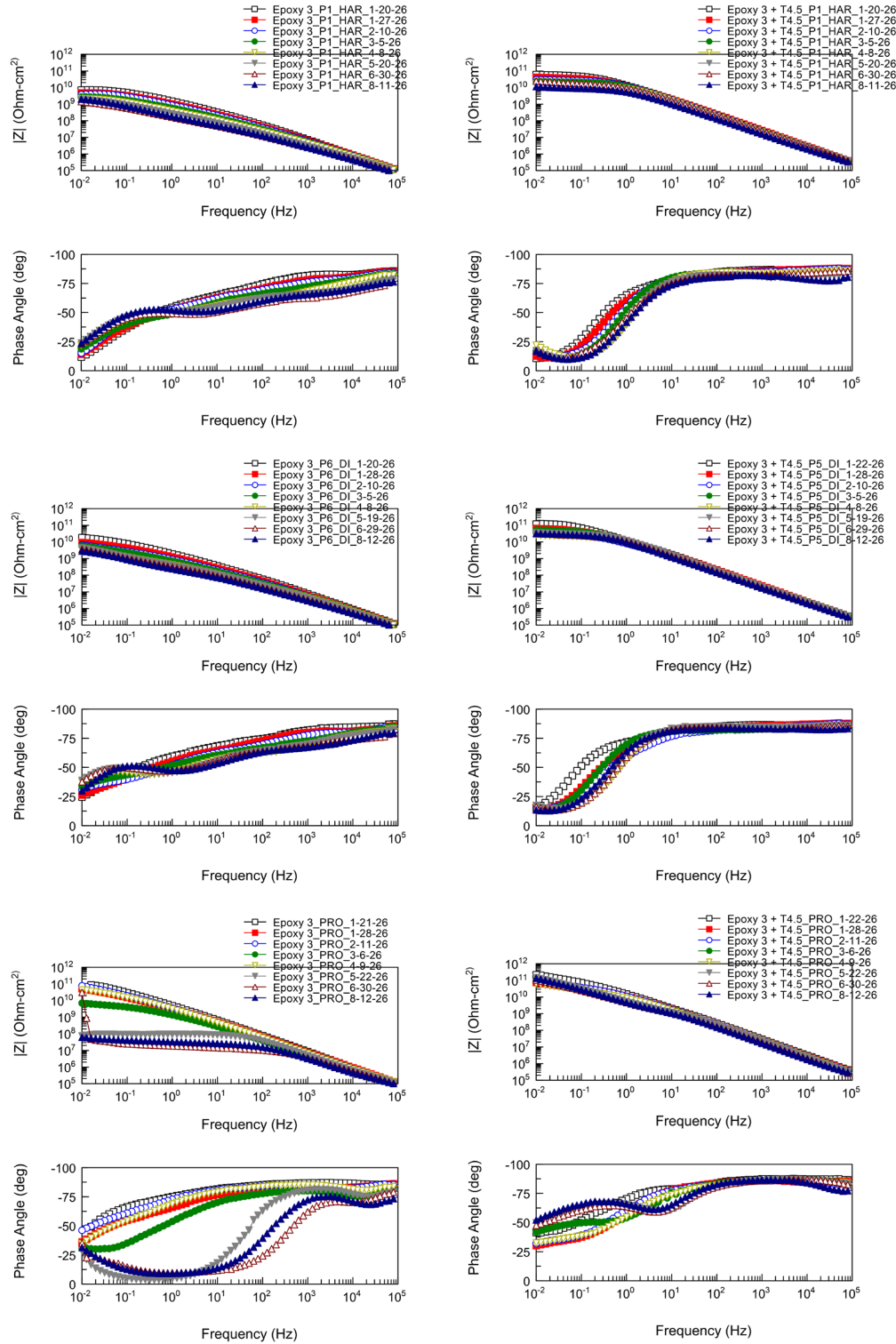


Figure D- 2. EIS of Epoxy 3 a) in HAR without and b) with T4.5 elastomer, c) in DI without and d) with T4.5, and e) in PRO with and f) without T4.5; DI without.

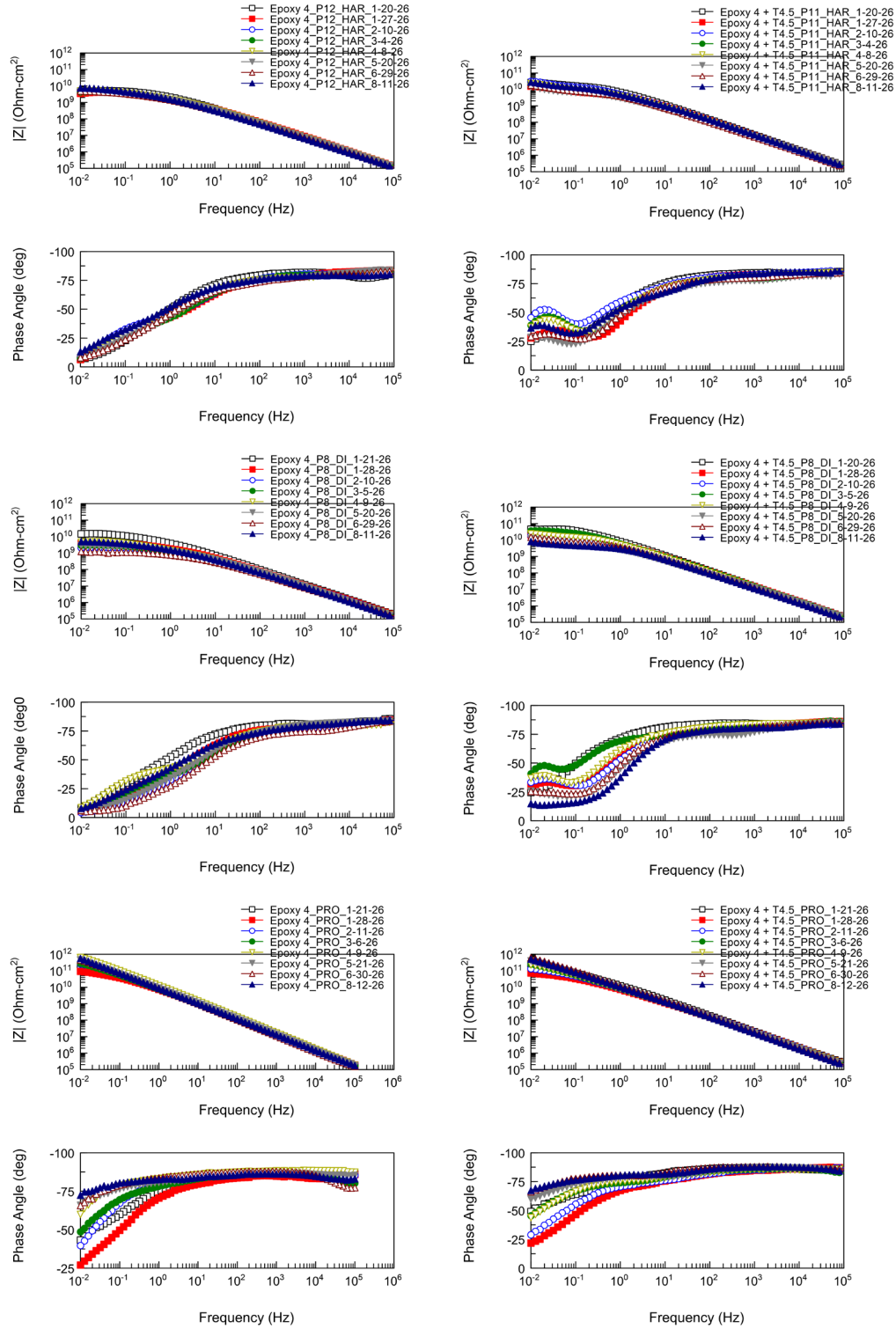


Figure D- 3. EIS of Epoxy 4 a) in HAR without and b) with T4.5 elastomer, c) in DI without and d) with T4.5, and e) in PRO with and f) without T4.5; DI without.