BUREAU OF RECLAMATION

Laboratory Evaluation of Field Repairable Materials and Techniques for Cavitation Damage: Phase II

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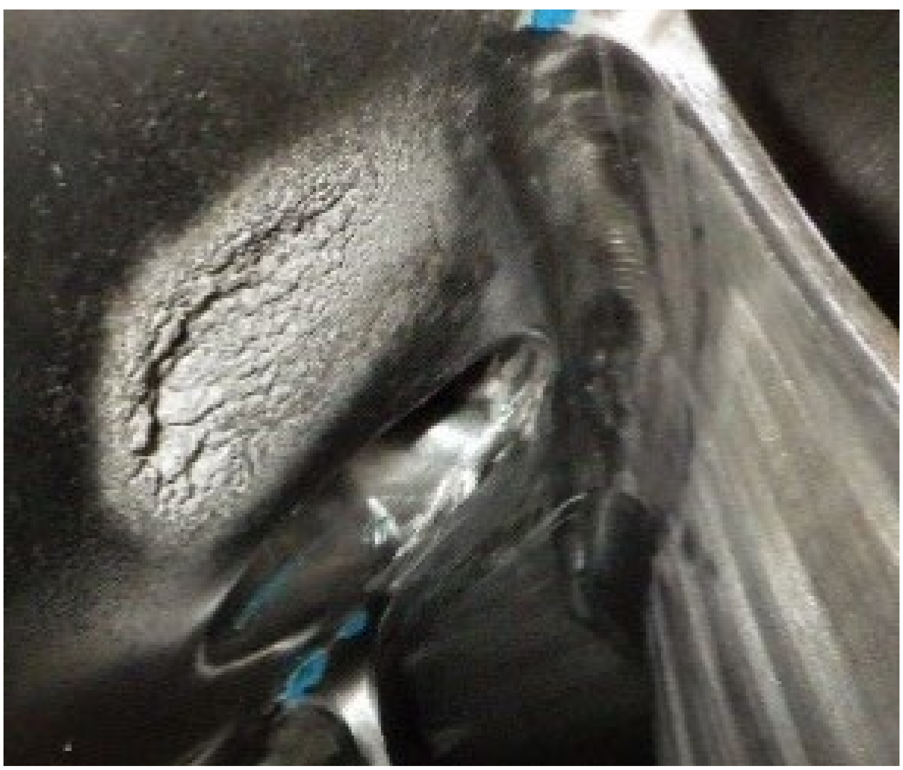
Final Report No. ST-2023-20024-01



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14. ABSTRACT
Cavitation resistant coatings have been used in mild cavitation conditions with mixed results and rarely are in service more than a few years before needing repair. Laboratory testing of two commercial polyurethane elastomers (polymers with rubber-like properties) provided superior cavitation resistance compared to prior coatings used in cavitating environments. These materials may provide protection in moderate or severe cavitating environments, comparable to stainless steel weld overlays. A field trial was deemed necessary to verify the outcomes of the laboratory findings. These two elastomers were selected for field trials on Nathaniel "Nat" Washington Power Plant Unit G21 turbine runner, a severe cavitation environment. Turbine runners have higher intensity cavitation and the commonly used stainless steel weld overlays eventually cavitate with significant pitting, requiring repair on a three-year rotation. Initial results showed a small area of damage in the most severe cavitation location near the leading edge on the suction side of the blade.

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Cover Photo: Cavitation damage on a turbine runner (Photo credit: Reclamation).

Peer Review

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Laboratory Evaluation of Field Repairable Materials and Techniques for Cavitation Damage: Phase II

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Acronyms and Abbreviations

DFT	dry film thickness
DOI	Department of the Interior
FIST	Facilities Instructions, Standards and Techniques
gpm	gallons per minute
hrs	hours
HVOF	high velocity oxygen fuel
kg	kilogram
mm	millimeter
mm^2	millimeter squared
mm^3	millimeter cubed
PE	polyurethane elastomer
PNNL	Pacific Northwest National Laboratory
psi	pounds per square inch
Reclamation	Bureau of Reclamation
S&T	Science and Technology
sq ft	square foot
TSC	Technical Service Center
U.S.	United States
USACE	United States Army Corps of Engineers

Definitions

Cavitation: The formation and subsequent collapse of vapor pockets in flowing liquid.

Cavitation Number: The change in pressure divided by the liquid density and flow velocity squared.

Discharge Factor: Operating condition volume of water passing through the turbine runner

Partial Vacuums: Areas of low pressure in flowing water.

Saturated Vapor Pressure: Pressure exerted by the vapor over a liquid. The saturated vapor pressure is the point when the liquid phase and vapor/gas phase are in equilibrium. Vapor pressure is a function of temperature.

Impinging Jet: A high pressure jet of water created during the collapse of a cavitation bubble.

Submerged Cavitating Jet: A continuous, high-pressure liquid jet in which cavitation is induced by the nozzle design.

Stand Off Distance: The distance between the inlet edge of the nozzle and the target face of the specimen.

Mild Cavitation: Cavitation intensity that damages most polymeric coatings and causes gradual cavitation damage to mild steel within 200 hours of laboratory testing or an estimated 10,000 hours of field operations.

Moderate Cavitation: Cavitation intensity that moderately pits mild steel but does not easily damage Type 308/309 stainless steel weld overlays within 200 hours of laboratory testing or an estimated 10,000 hours of field operations.

Severe Cavitation: Cavitation intensity that severely pits mild steel and moderately pits in Type 308/309 stainless steel weld overlays within 200 hours of laboratory testing or an estimated 10,000 hours of field operations.

Extreme Cavitation: Cavitation intensity that severely pits Type 308/309 stainless steel, and moderately damages Type 316 stainless steel within 200 hours of laboratory testing or an estimated 10,000 hours of field operations.

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Executive Summary

The Bureau of Reclamation (Reclamation) generates power and collects, conveys, and stores water by using structures such as pipelines, hydro-turbines, pumps, draft tubes, and outlet pipes. As a result of the high flow rates and pressure changes that occur in these structures, they can be subject to cavitation damage. Currently, Reclamation's primary method for mitigating cavitation is the use of stainless steel weld overlays. These repair methods are time-consuming, with some instances requiring outages of up to six months. Weld overlays have a finite service life, typically requiring repair every three years. On hydropower units, the repair costs are $100,000–$250,000 every 1–3 years per unit. As a result of these factors, cavitation damage has been identified as one of the most expensive maintenance items for Reclamation. Reducing the effects of cavitation on Reclamation structures will greatly reduce cost, both in repairs and equipment downtime.

The objective for this research was to identify a list of candidate repair materials that could be used to help lengthen the time between cavitation repair cycles. Researchers developed the Submerged Jet Test, a laboratory test method which uses a cavitating water jet to impinge samples at a 30-degree angle. The test apparatus applied severe cavitation to evaluate five metals and 22 polymeric coatings in the impact zone with 1450 pounds per square inch of pressure, 3.5 gallons per minute flow rate, and a cavitation number of 0.013. The laboratory results suggest the new test method produces results that are similar to severe cavitation conditions observed in the field. Testing showed two polyurethane elastomers, PE 1 and PE 2, resist moderate cavitation and could reduce galvanic corrosion between Type 308/309 stainless steel and mild steel. The field trials will determine the extent to which these materials reduce cavitation damage and corrosion.

<u>Laboratory Cavitation Testing Results</u>

- Type 316 stainless steel exhibited no measurable metal loss with only light frosting after 250 hours.
- Type A36 mild steel exhibited initial signs of pit formation at 16 hours and accumulated 180 cubic millimeters (mm^3) of material loss at 250 hours.
- Type 308/309 stainless steel weld overlay exhibited initial signs of pit formation at 40 hours and accumulated 6 mm^3 of material loss at 250 hours.
- Cavitec, a proprietary stainless steel alloy, showed no metal loss at 250 hours, but cracked in the cavitation and impact zone. Cracking is an unacceptable result as it can cause an electrolytic pathway to the substrate and result in galvanic and crevice corrosion of the mild steel substrate.
- Cold spray-applied Inconel 425 and CRC-410-1 chromium carbide tested with three different application parameters exhibited no metal loss at 250 hours, performing better than Type 308/309 stainless steel and showing less frosting than Type 316 stainless steel.

- The first round of testing showed that many commercial epoxy and polyurethane coatings have poor cavitation resistance. Two polyurethane elastomer (PE) materials were the best-performing non-metallic coatings in cavitating water-jet testing. Products PE 1 and PE 2 typically show no damage for 100-150 hours in severe cavitation conditions (impact and cavitation zones). Several of the sample failures occurred abruptly with sudden substrate exposure occurring near 250 hours.
- Follow-up laboratory testing showed these materials have good repairability, with abrasive blast cleaning required to prevent delamination at terminations. For initial findings, PE 1 required a minimum of 28 mils and PE 2 required a minimum of 21 mils to achieve cavitation resistance.

<u>Field Cavitation Testing Results and Conclusions</u>

Initial field trials of PE 1 and PE 2 at the Nathaniel “Nat” Washington Power Plant Unit G21 turbine runner resulted in a small region of elastomer failure after less than 1,000 hours of operation near the inlet on the suction side of the blade. This is the most severe cavitation zone of the runner, and estimated damage area for PE 1 and PE 2 were about 1 square foot (sq ft) and 10 sq ft, respectively. The field trials showed the PE coatings are difficult to apply and require pre-heating to lower the viscosity for mixing. The materials must also be hand-applied by trowel quickly after mixing. The pot life for PE 1 and PE 2 is 13 and 45 minutes, respectively. Spray-applied PE materials would provide an opportunity to improve application quality and reduce labor.

The exact time of failure was not determined. The unit was in service for 1,000 hours before the inspection could occur, and the time of the failure during that service period is unknown. The field test and the submerged jet test both damaged PE 1 and PE 2 in less than 1,000 hours, suggesting the lab test applies a similar level of severity and cavitation failure mode as produced in the severe cavitation zone of the Unit G21 turbine runner. PE 1 and PE 2 were undamaged by cavitation on the remaining runner blade in mild and moderate cavitation conditions. Long term performance will be evaluated at future inspections to determine if these materials reduce the extent of cavitation repairs required.

1. Introduction

1.1 Cavitation Background

In high-velocity liquid flows, a deterioration process called cavitation can occur when the pressure suddenly drops near the saturated vapor pressure and creates small vapor pockets, also known as cavitation bubbles. When these cavitation bubbles enter an area of higher pressure, they implode [1]. This releases a shockwave of energy, creating sound and exposing the surrounding surfaces to an impinging jet, which microfractures material surfaces, eventually pitting materials [2]. Cavitation is a localized process, generally occurring in very specific locations, such as around hydropower turbine or pump impellor components (e.g., draft tubes, scroll cases, wicket gates, discharge ring, and stay vanes). Francis turbines suffer cavitation specifically on the leading edge, trailing edge, inner-blade, and travelling bubble with severe cavitation occurring in the band area between blades. Cavitation damage to turbine runners can be as high as 5 kilograms (kg) per cubic meter over 10,000 hours, with about 200 kg loss after two years of operation [3].

Cavitation damage in draft tubes primarily occurs within the top one foot, just below the runner, but random damage may also be caused lower down by the draft tube vortex, shown in Figure 1. This scenario is considered a moderate cavitation condition because stainless steel weld overlay is not damaged in this environment. Draft tubes occasionally contain recessed or raised objects for inspection ports or platforms, which can also cause cavitation downstream of these features.

Additionally, cavitation is observed on non-hydropower components, such as on the downstream side of valves or gates when high pressure water upstream side sprays past the seats or seals, or where a pressure drop occurs in high flow operations.

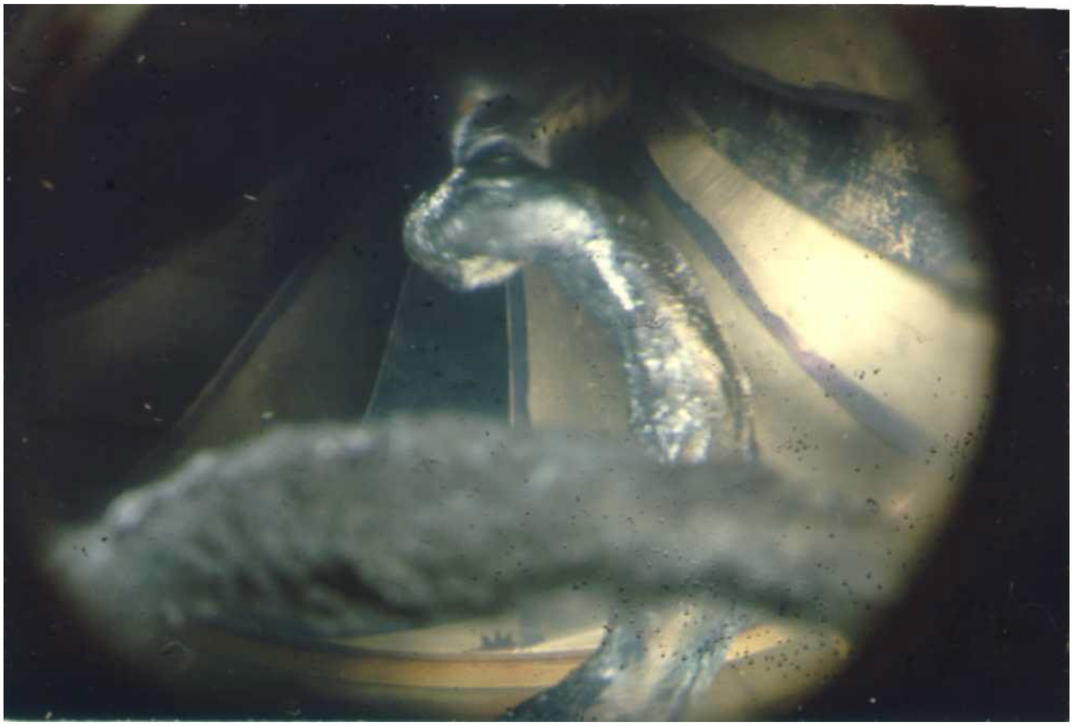

Figure 1.—Cavitation vortex in Nathaniel "Nat" Washington Power Plant Unit 21 draft tube.

The pitting rate caused by cavitation can increase with time due to increasing surface area which creates new areas of low pressure, further increasing the rate of damage. As cavitation damage of the material becomes more severe, equipment efficiencies decrease, sometimes wearing through the entire material thickness [2]. At that point, complete replacement or extensive repairs are required. Figures 2 and 3 show varying levels of cavitation damage in localized areas on a turbine runner, from areas with no cavitation and undamaged epoxy coating to areas with significant damage to the Type 309 stainless steel weld overlays. Grand Coulee does not utilize the Type 308 base weld. Costs of equipment repair, replacement, and downtime are high, estimated to be $100,000–$250,000 per unit every several years. Therefore, there is a great need to mitigate the effects of cavitation on hydraulic structures.

Figure 2.—Nathaniel "Nat" Washington Power Plant Unit G22 turbine runner with minimal damage to the Type 309 stainless steel weld overlay and some galvanic corrosion. The epoxy coating system failed due to cavitation. This blade location is a moderate cavitation environment.

Figure 3.—Nathaniel "Nat" Washington Power Plant Unit G21 turbine runner with cavitation pitting damage on the Type 309 stainless steel weld overlay penetrating through to the mild steel substrate. This blade location is a severe cavitation environment.

1.2 Cavitation Mitigation Methods using Stainless Steel

The primary method to mitigate cavitation is by replacing mild steel with stainless steel, primarily using alloy Type 304 stainless steel for turbine runners and CA-6NM for wicket gates per the Facilities Instructions, Standards and Techniques Manual, Volume 2-5 (FIST 2-5) [4]. Approximately 60 percent of Reclamation's turbine runners have been replaced with stainless steel alloy Type 304 or 308. However, 40 percent of Reclamation facilities still have mild steel runners and some require Type 308/309 stainless steel weld overlays for cavitation repair in accordance with FIST 2-5 [4]. The weld overlay procedure is time-consuming and expensive, with some instances requiring up to six-month outages and 2000 pounds of welding rods [3]. The welding process induces residual stress to the structure, creates a heat affected zone vulnerable to multiple types of failure, and creates a site for galvanic corrosion cells between the stainless steel and mild steel. Once cavitation pitting penetrates the stainless steel overlay, galvanic corrosion of the mild steel substrate causes disbonding of the overlay, further exposing the mild steel substrate to corrosion and cavitation damage, as shown in Figure 4. Thus, weld overlays have finite service lives and require periodic repair.

Figure 4.—Image of a Type 308/309 stainless steel weld overlay on cast steel in a draft tube that has failed by galvanic corrosion; cavitation damage is observed on the mild steel substrate.

1.3 Cavitation Mitigation using Coatings

1.3.1 Metallic Coatings

Another cavitation mitigation strategy uses metallic coatings, such as stainless steels or nickel alloys, applied to the base metal by thermal spray techniques: high velocity oxygen fuel (HVOF), plasma thermal spray, or electric arc thermal spray [5] [6] [7]. These application methods produce a porous coating and have not generally performed well for cavitation resistance [5]. Stellite applied by HVOF has shown the most success of the thermal sprayed materials in cavitation [5, 6, 8].

Recently an alternative weldable material became commercially available. Cavitec is a martensitic stainless steel that hardens with increased deformation [6]. Since Cavitec becomes harder with cavitation jet impingement, it is estimated to provide six times the service life compared to Type 308/309 stainless steel weld overlays [6].

Cold spray is a relatively new application technique for hard metals, such as Inconel. Pacific Northwest National Laboratory (PNNL) is developing a cold spray technique to apply a blend of Inconel 625 powder and CRC-410-1 chromium carbide particles to mild steel substrates. The laboratory results are promising, with test samples exhibiting three times better cavitation resistance than Type 316 stainless steel [7].

1.3.2 Polymeric Coatings

Many coatings manufacturers state cavitation resistance on product datasheets for materials that exhibit poor field performance and short service lives in most cavitation conditions. In the 1960s and the 1990s, Reclamation conducted cavitation research on polymeric coatings [8] [9] [10]. The 1960s research found a neoprene coating provided excellent cavitation resistance, but during field trials, the coating delaminated from the test structure. The 1990s research did not identify any coatings with cavitation resistance [11]. In recent years, multiple researchers outside of Reclamation focused on elastomeric coatings for cavitation resistance [12] [13] [14]. The research presented in this report focused on evaluating the cavitation resistance of ceramic-filled epoxies, polyurethane elastomers, and epoxy polysulfides. The U.S. Army Corps of Engineers vinyl System 5-EZ is used as a comparison material.

1.4 Degree of Cavitation

Severe cavitation conditions can cause damage to Type 308/309 stainless steel weld overlay and under extreme conditions damages 316 stainless steel. An example of severe cavitation damage on stainless steel is shown in Figure 5. Different levels of cavitation severity are defined for this research and summarized in Table 1 below and include in the Definitions section of this report.

Table 1.—Cavitation severity levels defined for this research based on the damage level observed in traditional polymer coatings, mild steel, Type 308/309, and 316-series stainless steels after 200 hours of laboratory testing or an estimated 10,000-hour exposure in the field.

Cavitation Intensity	Traditional Polymer Coatings	Mild Steel	Type 308/309 Stainless Steel	Type 316 Stainless Steel
Mild	Volume loss and some complete removal	Light frosting/ minor metal loss	No damage	No Damage
Moderate	Complete removal	Moderate metal loss	Light frosting	No Damage
Severe	Complete Removal	Severe metal loss	Moderate metal loss	Light frosting
Extreme	Complete Removal	Severe metal loss	Severe metal loss	Moderate metal loss

Figure 5.—Examples of extreme cavitation damage on Type 316 (left) and 304 (right) stainless steel turbine runners.

Cavitation intensity is determined by the vapor bubble diameter, flow velocity, cavitation number, discharge factor, and speed factor [15]. The cavitation number is the intensity calculated from the change in pressure divided by the liquid density and the velocity squared. The operating conditions such as the discharge factor (volume of water) and speed factor (flow velocity) influence the extent and location of damage. Cavitation resistance of materials is complex due to the hydrodynamics and the interaction of mechanical, metallurgical, and chemical factors, which makes it challenging to predict the material properties that most influence cavitation resistance.

1.5 Objectives and Scope of Research

Cavitation resistant coatings have been used in mild cavitation conditions with mixed results and rarely last more than a few years before needing repair. The objectives for this research were to develop a list of candidate coatings that could be used to help lengthen the time between cavitation repair cycles.

A dual protection method using traditional stainless steel weld overlay and a cavitation resistant coating that could potentially withstand severe cavitation environments would provide the longest service life for repairs on hydropower infrastructure such as turbine runners, draft tubes, valves, and gates. For this research, the focus was on polymeric materials, specifically ceramic-filled epoxy and elastomeric materials. Additionally, two new metal repair materials were evaluated, one weldable metal and a cold spray material.

The summarized scope of this research, which is described fully within this report, can be broken into the following pieces:

1. Develop a new laboratory test method for cavitation testing.
2. Prepare test samples and perform baseline testing to refine laboratory set-up.
3. Perform initial laboratory testing, evaluate results, and select high-performing materials for further testing.
4. Perform follow-up laboratory testing on the selected materials using identified critical objectives to compare to Type 308/309 stainless steel weld overlay experimental control.
5. Apply the selected materials to structures in field service to begin field trials.

1.6 Parallel Research

Erosion is another severe service condition that limits the service life of coatings. A select number of ceramic-filled epoxies and polyurethane elastomers were evaluated in laboratory erosion testing for the ongoing S&T project 21005, Abrasivity of Slurry-Transported Sediment: Development of a Laboratory-Based Test System. A paper and presentation combining initial results of cavitation and erosion testing was given at the 2023 AMPP conference and is attached in Appendix A [16].

2. Laboratory Testing Methods

2.1 Materials

Laboratory testing included 27 materials in three categories: metallic, ceramic-filled epoxy, and elastomeric coatings. The metallic samples were used for baseline measurements during refinement of the laboratory test set-up to determine appropriate water flow levels to provide the desired cavitation conditions. This is further described in Section 2.2.2. The test materials are listed by category below:

<u>Metallic</u> (5)

- A36 mild steel
- Type 316 stainless steel
- Type 308/309 stainless steel weld overlay
- Inconel 625 blended with CRC-410-1 chromium carbide powder applied by cold spray
- Cavitec weld overlay

<u>Ceramic Epoxy</u> (12)

- Ceramic-filled epoxies 1–12

<u>Elastomeric</u> (10)

- Polyurethane elastomers 1–8
- Polysulfide epoxies 1–2

2.2 Sample Preparation and Cavitation Testing

Samples of the polymeric coatings were prepared from 4-inch by 6-inch by 0.75-inch mild steel coupons. Three replicates of each system were prepared by solvent cleaning the coupons to SSPC-SP1, followed by abrasive blast cleaning to SSPC-SP5 white metal using LG 25 steel grit to generate a 3.5-mil minimum surface profile [17] [18]. The coatings were either applied in accordance with manufacturer's instructions or were shipped to the manufacturer for coating application. The coated samples were preconditioned in water immersion for at least 2 weeks prior to testing.

Cavitec was welded by the manufacturer on a mild steel substrate. The 0.125-inch-thick weld overlay was machined to provide a smooth test surface.

A blend of Inconel 625 and CRC-410-1 chromium carbide was applied in a 0.0625-inch-thick layer by cold spray using proprietary application parameters to 316 stainless steel substrate, prepared by PNNL.

Type A36 mild steel and Type 316 stainless steel samples were machined to form a smooth surface, and solvent cleaned to SSPC-SP1 [19].

The Type 308/309 stainless steel weld overlay was completed by a facility in Reclamation by welders that typically perform cavitation repairs. A layer of Type 308 is welded to mild steel for better adhesion followed by Type 309 stainless steel welded on top the Type 308 stainless steel for the cavitation resistance. The Type 308/309 stainless steel was machined to form a smooth surface, and solvent cleaned to SSPC-SP1 [19].

Researchers found that evaluating coatings by the existing standard test procedures for evaluating cavitation performance were not appropriate for testing polymeric coatings. ASTM G134, Standard Test Method for Erosion of Solid Materials by Cavitating Liquid Jet, is aimed at evaluating metals [20]. The specimen size is small, with a 12-millimeter (mm) diameter, and the test uses a jet with a 90-degree impingement angle. The sample size makes proper surface preparation and coating application extremely challenging. ASTM G32, Standard Test Method for Cavitation Erosion using Vibratory Apparatus, which is more suited to coating evaluation, specifically excludes elastomers from the acceptable test materials [21].

To overcome these challenges, researchers developed a new cavitation submerged jet test method to evaluate coatings in a way that allowed for testing many different materials with multiple replicates [22]. The new test method has a larger damage area compared to other cavitation tests. The submerged jet test also allows for adjustment of the cavitation intensity to target a desired level of damage.

2.2.1 Submerged Jet Test Method

Researchers developed a new cavitation test method to optimize for testing of coating materials. The new test method induces cavitation using a submerged jet, similar to the method described in ASTM G134 [20]. Whereas ASTM G134 uses a jet with a 90-degree impingement angle, the submerged jet test method places the specimen at a 30-degree angle to the jet, as explained below. The testing apparatus consists of a 10-horsepower 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 nozzles, a sample holder, and a 120-gallon water tank with a clear viewing window [22] [23].

Samples are installed in a sample holder with a 30-degree angle from the nozzle. The angle allows the cavitation cloud to flow down the sample to optimize the area affected by cavitation bubble implosion, as shown in Figure 6. The angle also minimizes other physical mechanisms that may cause damage and/or wear to the surface of the sample (e.g., erosive hydrodynamic impact and shear forces). 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 DASYlab software. The test procedure is set at 1,450 ± 25 pounds per square inch (psi) and 3.5 gallons per minute (gpm) flow rates. Nozzle calibration is to be performed periodically throughout testing. Atmospheric pressure and water temperatures are recorded daily during each test.

As shown in Figure 6, there are two cavitation zones on the samples, the impact zone and the pure cavitation zone. The impact zone contains jet impact pressures and velocities along with cavitation on the sample. The pure cavitation zone is where cavitation implosions occur when the cloud travels down the sample.

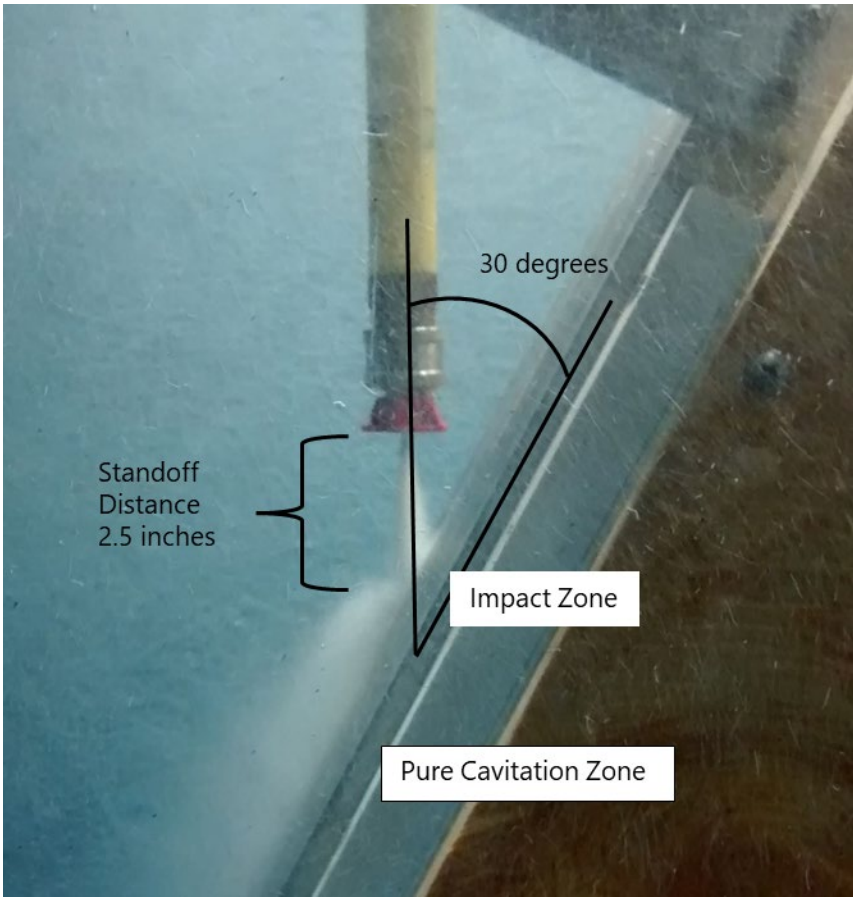

Figure 6.—Image of submerged jet cavitation testing showing the sample angle with the cavitation travelling down the sample, along with the location of the two defining zones of damage.

The tank is filled with water and open to the atmosphere. The submerged jet flow rates and pressures are monitored throughout the test to calculate the cavitation number. For the purposes of this laboratory testing, the cavitation number was held constant at 0.0129 ± 0.0002. Samples are tested for eight hours each day and evaluated frequently throughout the day. If failure to the substrate occurred, the sample was removed from testing. Samples were tested for up to a total of 40 hours before the test was terminated. With the two separate test apparatuses, two specimens can be tested simultaneously, as shown in Figure 7.

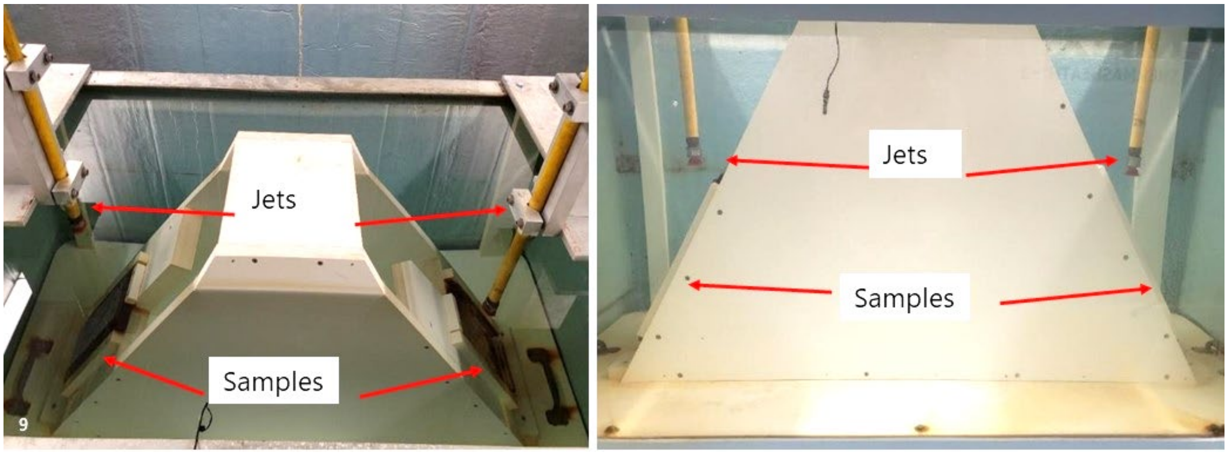

Figure 7.—Top view (left) and side view (right) of submerged jet test set-up.

2.2.2 Baseline Testing of Metals

To determine levels of water flow to achieve the desired degree of cavitation and verify the desired extent of damage, researchers performed baseline testing on materials typically used for cavitation repair. The set-up for baseline testing was the same as described in Section 2.2.1. The baseline materials included Type A36 mild steel, Type 316 stainless steel, and Type 308/309 stainless steel.

During baseline testing, researchers optimized the test procedure to cause light frosting damage to 316 stainless steel and moderate pitting to mild steel in 40 hours of exposure, shown in Figure 8. Figure 9 shows light frosting to a 308/309 stainless steel weld overlay sample in a 40-hour period of exposure in the optimized test procedure. This baseline testing informed the selection of the test parameters (pressure: 1,450 ± 25 psi, flow rate: 3.5 gpm, and cavitation number: 0.0129 ± 0.0002), which caused initial cavitation damage on mild steel in 16 hours of testing and measurable damage in 40 hours of testing, shown in Figure 10.

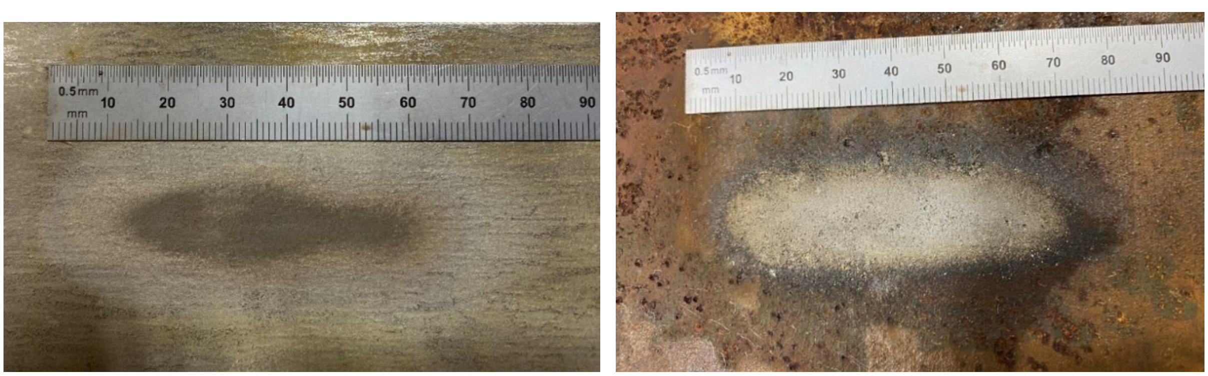
Figure 8.–Type 316 stainless steel (left) and mild steel (right) after 40 hours exposure to submerged jet testing. Notice pitting caused by cavitation in the mild steel. Ruler tick marks are in millimeters.

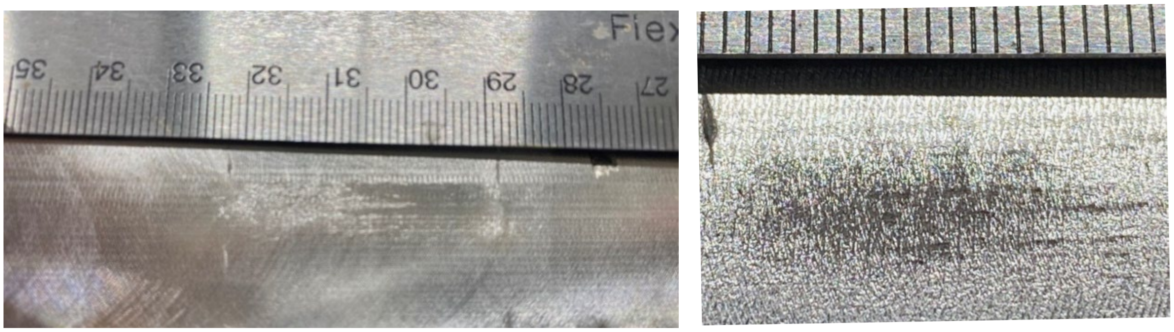

Figure 9.—Photo of Type 308/309 stainless steel weld overlay after 40 hours of exposure to the submerged jet testing (left) and close-up image (right). The damaged area is significantly less than mild steel. Ruler tick marks are in millimeters.

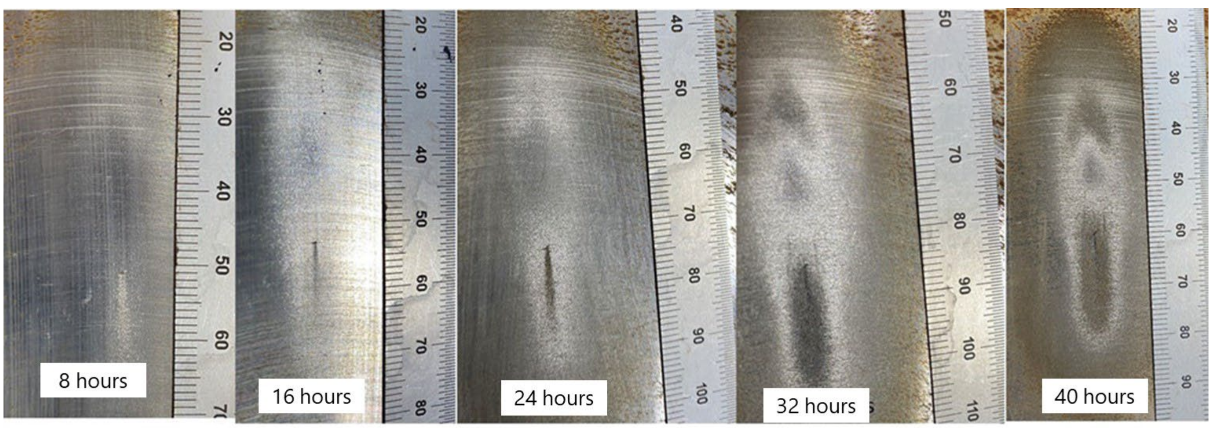

Figure 10.—Baseline testing of mild steel and progression of cavitation damage after increasing 8-hour test periods, shown from left to right. Ruler tick marks are in millimeters.

2.2.3 Evaluation of Materials

The baseline testing established a criterion for determining if materials can withstand severe cavitation environments: materials must pass 40 hours of the submerged jet testing to be considered comparable to a Type 308/309 stainless steel weld overlay. For only mild cavitation resistance, this might require materials to show no damage between 8–30 hours.

During testing, researchers found that weight loss was not an effective method to evaluate coatings. Some coatings abruptly failed in a short period of time, or in the case of elastomeric materials, the coating tore from the substrate. Material loss could not be established in these situations. Therefore, time to failure to substrate was used to compare materials. For metallic samples, volume loss was monitored over time using a laser scanner (Faro Quantum S Arm with V6 FAROBlu HD Laser Line Probe).

3. Laboratory Test Results and Discussion

3.1 Metallic Repair Materials

Three metallic repair materials were evaluated, Type 308/309 stainless steel weld overlay, Cavitec weld material, and cold spray-applied Inconel 625/CRC-410-1 chromium carbide powder. All metallic samples had no or minimal damage at 40 hours and were further evaluated during long-term testing.

3.2 Ceramic Epoxy Coatings

The twelve ceramic-filled epoxy coatings evaluated failed in relatively short periods of time, as shown in Figure 11. For most of these systems, only one sample was evaluated due to the poor performance, and therefore only a few samples show the calculated average with a standard deviation.

The worst-performing epoxy (Ceramic Epoxy 6) failed within 45 minutes. The best-performing epoxy was Ceramic Epoxy 7. It was also the thickest coating, exceeding 250 mils, which contributed to the long performance. During initial laboratory testing, researchers quickly concluded that epoxy systems do not provide long-term cavitation resistance. All ceramic-filled epoxy samples exhibited inferior performance to mild steel, which first showed damage at 16 hours during baseline testing and is known to cavitate in moderate conditions in hydropower plants. These findings are consistent with observations from field installations where ceramic-filled epoxies in service have historically lasted for less than one year in mild cavitating environments.

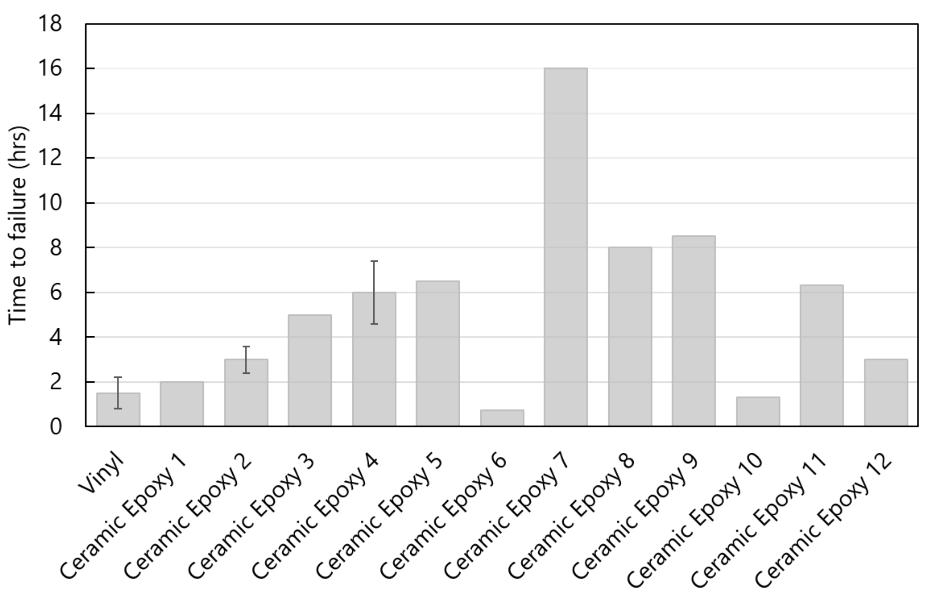

Figure 11.—Cavitation resistance of ceramic-filled epoxy, time to failure in hours (hrs).

3.3 Elastomeric Coatings

Results from the eight polyurethane elastomers, denoted PE 1–PE 8, and two polysulfide epoxy elastomers evaluated are shown in Figure 12. The worst-performing elastomer was Polysulfide Epoxy 1 which failed within 4 hours on average. PE 3, PE 4, PE 6, and PE 7 failed within 8 hours on average. PE 7 has been used in Reclamation draft tubes with good results in mild cavitating environment in the field, but usually fails in the top one foot of the draft tube in moderate cavitation. PE 8 has been used on turbine runners and pump impellors in European countries with success but failed within 16 hours of testing [24]. The best-performing materials were PE 1, PE 2, and PE 5, which passed the initial 40-hour test. Both PE 1 and PE 2 showed minimal damage at 40 hours. PE 5 had more damage than PE 1 and PE 2 but did not fail to the substrate.

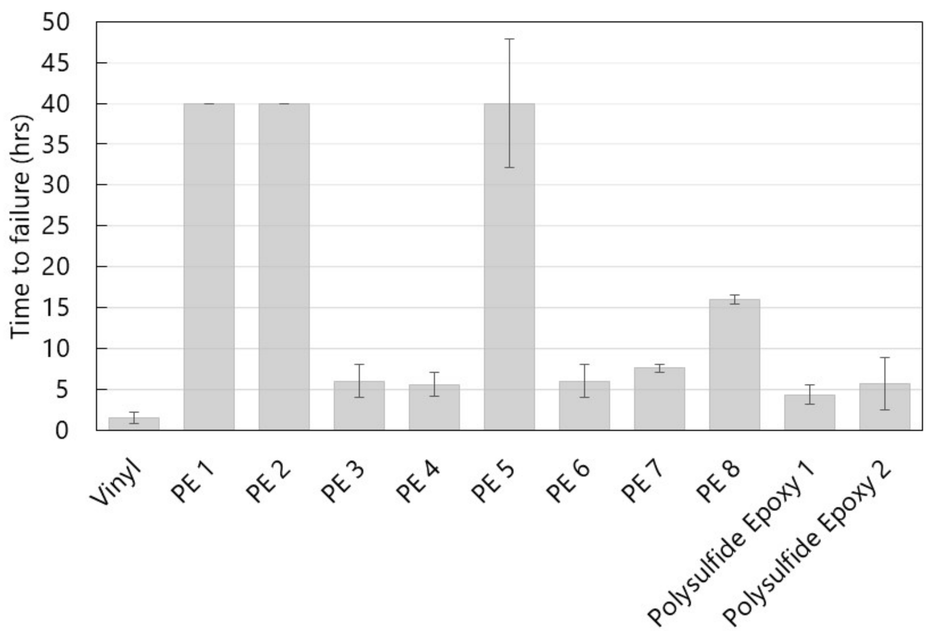

Figure 12.—Cavitation resistance of elastomeric coatings from laboratory testing with time to failure in hours (hrs).

4. Follow-up Laboratory Testing

Coating materials that passed 40 hours of submerged jet cavitation testing were selected for further evaluation in follow-up testing. Follow-up testing included both extended laboratory testing, as well as field trials, which are described in Section 5.

To help guide follow-up testing, prior to moving forward to field trials researchers came up with the following list of critical objectives and associated questions to consider during planning:

- **Ease of Coating Repairability-** what preparation and application procedures should be followed by facility maintenance personnel to produce effective repairs?
- **Effect of Termination Details-** how must the repair edge be terminated to prevent loss of adhesion to the substrate in high velocity water flow?
- **Minimum Coating Thickness Requirements-** what is the minimum coating thickness required to absorb the cavitation energy without damage?
- **Long-term Testing-** how do the repair materials resist severe or extreme cavitation for greater lengths of time than what is achieved by traditional repair materials (i.e., Type A36 mild steel, Type 316 stainless steel, and Type 308/309 stainless steel weld overlay)?
- **Cavitation Intensity** – Do the polyurethane elastomers resist damage with increasing cavitation intensity?

For each critical objective, the materials selected for follow-up testing and the methods for that testing are described in the following subsections.

4.1 Ease of Coating Repairability

Cavitation damage will always eventually fatigue materials, requiring repairs. So, it is vital to verify that repairs will be effective and adhere to the existing coating. It must also be possible for the repairs to be performed by Reclamation maintenance personnel, who are responsible for conducting repairs as needed over the life of the structure.

For this testing, PE 1 was evaluated for repairability. PE 7 was used underneath the repair as the existing coating since Reclamation has used it in draft tubes. Prior samples of PE 1 were prepared using various power tool cleaning methods—needle gun, angle grinder, and bristle blaster—along with abrasive blast cleaning. Outcomes from testing showed that repairs with each power tool cleaning technique were equally successful, surviving 40 hours of cavitation testing. Researchers had no concerns that Reclamation personnel could make the repairs with proper training.

4.2 Effect of Termination Details

The termination details and surface preparation type are important for successful cavitation performance. The water around cavitating environments is turbulent with high water velocity. The termination details may prevent delamination or further cavitation from occurring. Any slight offset will cause cavitation to occur downstream.

For this testing, PE 1 was applied with two distinct termination details—either a blunt edge with 30-mil thickness or tapered to no thickness (troweled smooth). The termination was placed at the point of cavitation jet impact. The test samples were prepared from 4-inch by 6-inch by 0.75-inch-thick mild steel coupons.

Different surface preparation methods were investigated using an angle grinder, bristle blaster, and abrasive blast cleaning to determine if disbondment of PE 1 could occur. For power tool cleaning, three replicates were prepared for each type of power tool cleaning method. Samples were prepared by solvent cleaning to SSPC-SP1, followed by power tool cleaning to bare metal SSPC-SP11 using needle guns, angle grinders, and bristle blaster [17] [19]. For abrasive blasting, three replicates were prepared by solvent cleaning to SSPC-SP1, followed by abrasive blast cleaning to SSPC-SP5 white metal using LG 25 steel grit to generate a 3.5 mil minimum surface profile [17] [18]. The profile for the other methods were 0.5 mils for angle grinder and needle gun and 1.0 mil for the bristle blaster. Results are shown in Figure 13.

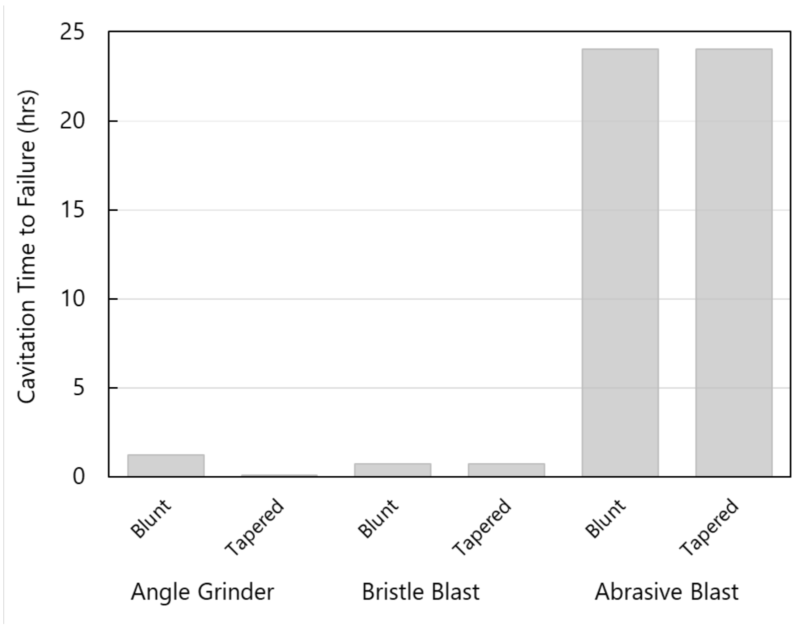

Figure 13.—The effect of different termination details on cavitation time to failure in hours (hrs) for PE 1. Abrasive blast cleaning is necessary to prevent delamination.

The results found that the power tool-cleaned surfaces (angle grinder and bristle blast) did not provide adequate adhesion along the termination points, resulting in delamination within a relatively short period of time. Therefore, abrasive blast cleaning is the recommended approach for the elastomer to have adequate adhesion. Visually, the blunt edge appearance looked cleaner, and thus may be preferred from an aesthetic standpoint, although the blunt and tapered edges had equal performance for the abrasive blast trial.

4.3 Minimum Coating Thickness Requirements

Polyurethane elastomers appear to require a minimum coating thickness to absorb the cavitation energy. The PE 1 product datasheet states that it requires 30 mils minimum dry film thickness (DFT). PE 2 was not designed for cavitation resistance, and there is no data for a minimum thickness.

This testing investigated different elastomer thicknesses for PE 1 and PE 2 to determine the minimum coating thickness to obtain cavitation resistance up to 40 hours exposure. Samples were 4-inch by 6-inch by 0.75-inch-thick mild steel coupons. Three replicates were prepared by solvent cleaning to SSPC-SP1, followed by abrasive blast cleaning to SSPC-SP5 white metal using LG 25 steel grit to generate a 3.5-mil minimum surface profile [17] [18]. Coatings were applied using a draw down bar to three different DFT levels: 6–8 mils, 16–21mils, and 28 mils. Results are shown in Figure 14.

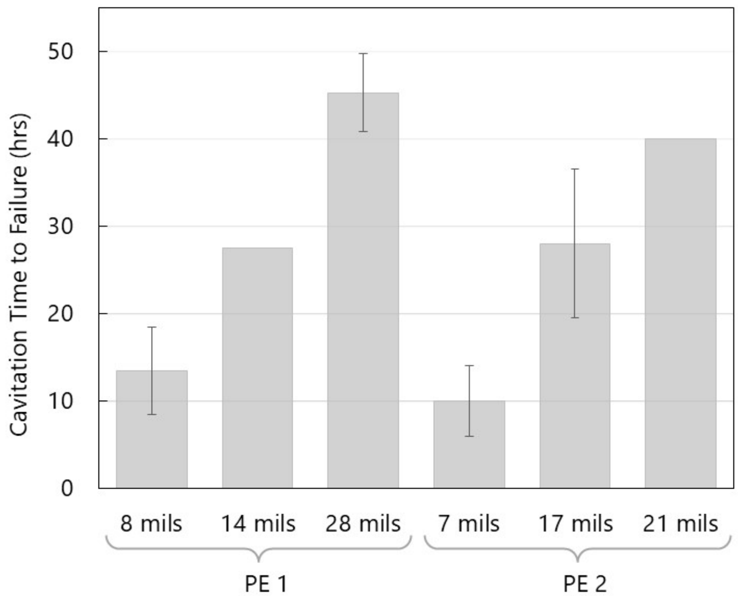

Figure 14.—Elastomer thickness study to determine the minimum elastomer thickness to resist cavitation with time to failure in hours (hrs).

To achieve cavitation resistance for at least 40 hours of exposure, the manufacturer's recommended thickness is needed. Further, the results suggests that cavitation performance increases with coating thickness and that a minimum thickness is needed for elastomers to absorb the cavitation energy. Further testing would be needed to confirm this and to determine if there is a maximum thickness where cavitation resistance declines.

4.4 Long-term Testing

Long-term testing evaluated the best performing coatings (PE 1 and PE 2) for a total of 250 hours. Results were directly compared to mild steel, Type 316 stainless steel, and Type 308/309 stainless steel weld overlay. This allowed researchers to determine how effective these coatings could be in the long term on structures subjected to severe or extreme cavitation. Additionally, other metallic repair materials (Cavitec and three cold spray samples) were evaluated for long-term testing.

Test samples were 4-inch by 6-inch by 0.75-inch-thick mild steel coupons. Two replicates of each system (indicated by -1 and -2) were prepared by solvent cleaning to SSPC-SP1, followed by abrasive blast cleaning to SSPC-SP5 white metal using LG 25 steel grit to generate a 3.5 mil minimum surface profile [17] [18]. PE 1 was applied in accordance with manufacturer's instructions. Based on the initial laboratory testing, PE 2 required improved adhesion to the substrate, and researchers decided to use the PE 1 primer system for PE 2. Normally, intermixing manufacturers' products is not recommended. But based on the reported coating chemistries, the researchers were confident that the combination of these products would result in the desired intercoat adhesion and a cured product.

Samples were periodically analyzed using a laser scanner to monitor volume loss over time. Outcomes for each material are in the following subsections, including representative photographs and laser scanner results. Each scan with the laser scanner is overlayed on the last to show surface changes and determine depth of pitting over time.

Summarized results of volume loss over time are shown in Figure 15. The plot suggest that the metals lose material at different rates, with mild steel losing the most volume of the metals. The elastomers do not show a consistent trend in the available data, even between replicates. For example, PE 1-1 showed volume loss at 200 hours that was unchanged at 250 hours while PE 1-2 lost minimal volume over the test period and then abruptly failed to the steel substrate at 250 hours. Further testing could establish volume loss rates and variability for each material.

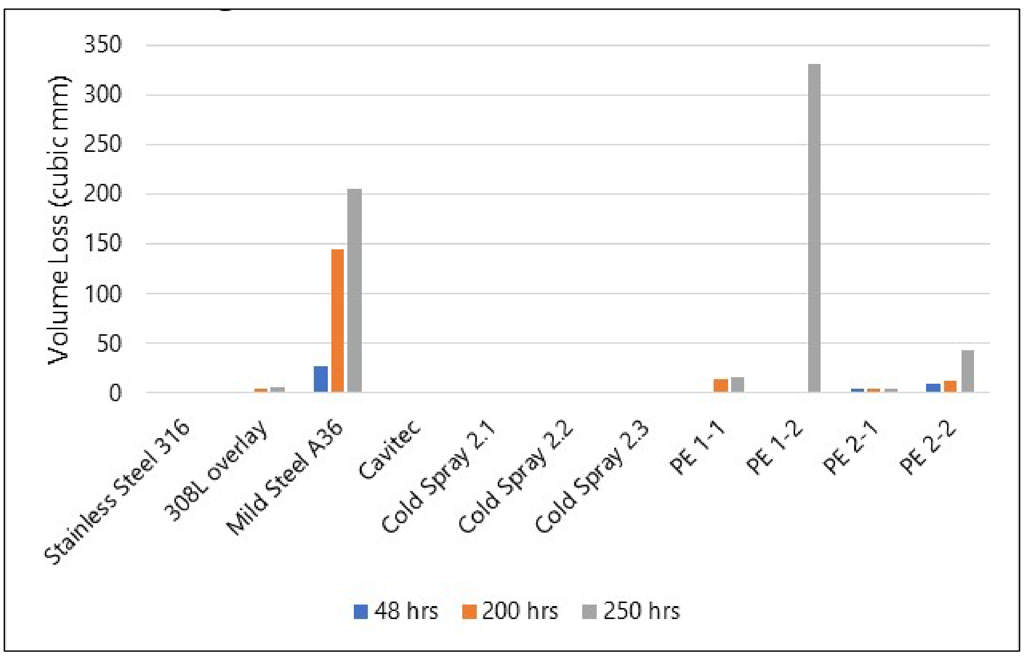

Figure 15.—Long-term testing to evaluate the top performing materials for three test durations reported in hours (hrs).

4.4.1 Baseline Materials

316 stainless steel and A36 mild steel were used as baseline materials and 308/309 stainless steel weld overlay was used as the baseline repair material. Type 316 stainless steel had no metal loss after 250 hours, but minor visible frosting was apparent shown in Figure 16. Type A36 mild steel lost 181.4 mm^3 of volume after 250 hours with the max depth of 1 mm in the pure cavitation zone and a total damage area of approximately 1500 millimeters squared (mm^2) surface area as seen in Figure 17. Type 308/309 stainless steel lost 5.8 mm^3 of volume after 250 hours with a maximum depth of 0.3 mm as observed in Figure 18.

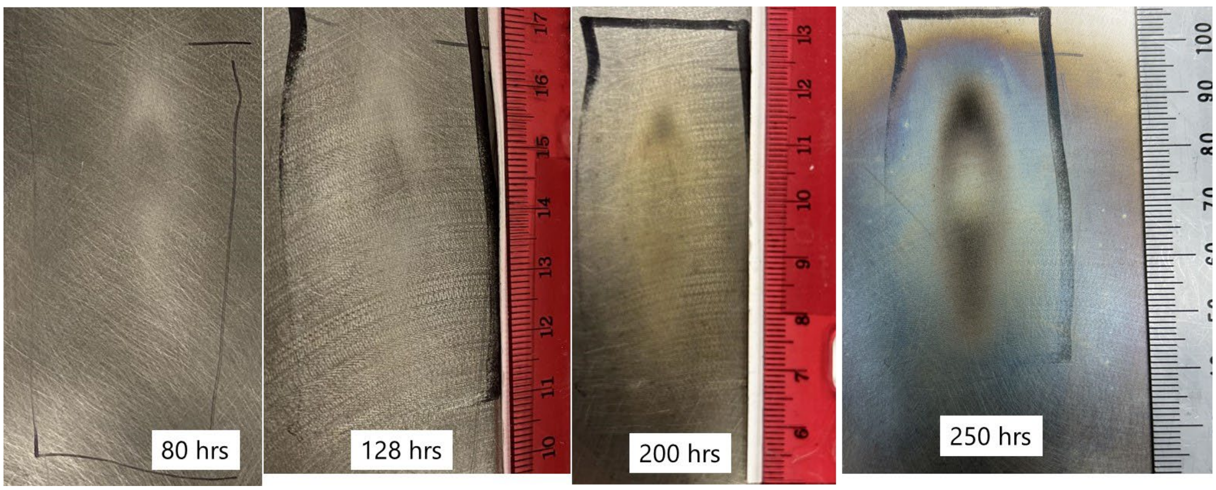

Figure 16.—Type 316 stainless steel long-term cavitation testing results: visible frosting, but no measurable material loss was observed. Ruler tick marks are in millimeters.

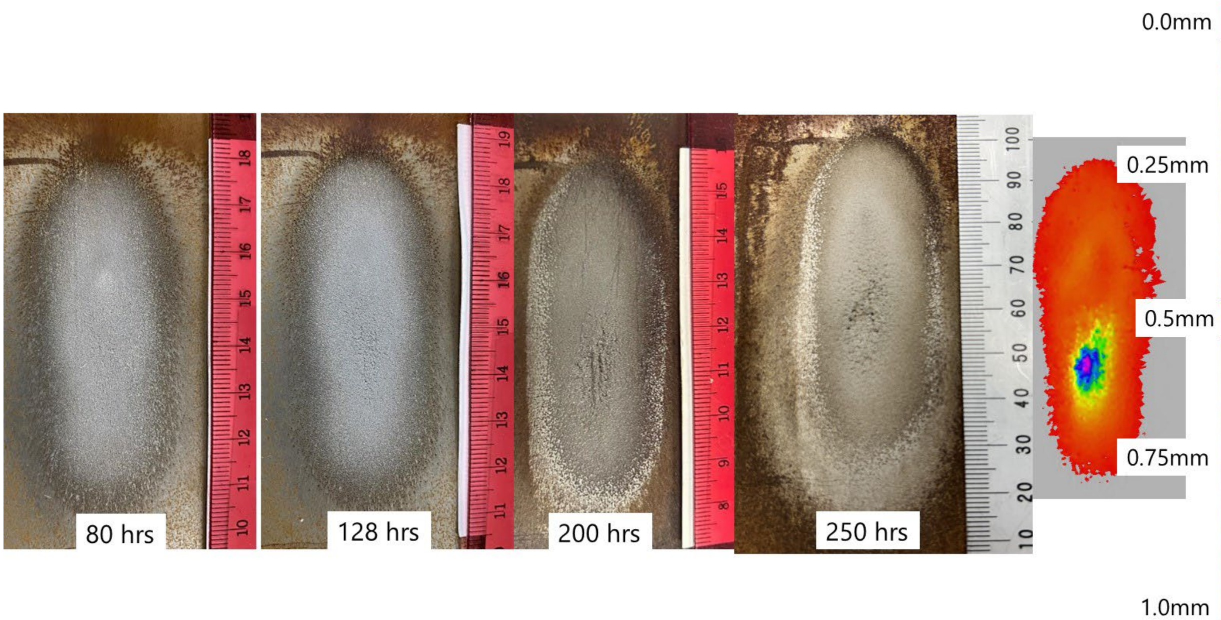

Figure 17.—A36 mild steel long-term cavitation testing results: visible pitting and metal loss was observed. The image to the right was developed from the laser scanner to show the volume and depth loss at 250 hrs. Ruler tick marks are in millimeters.

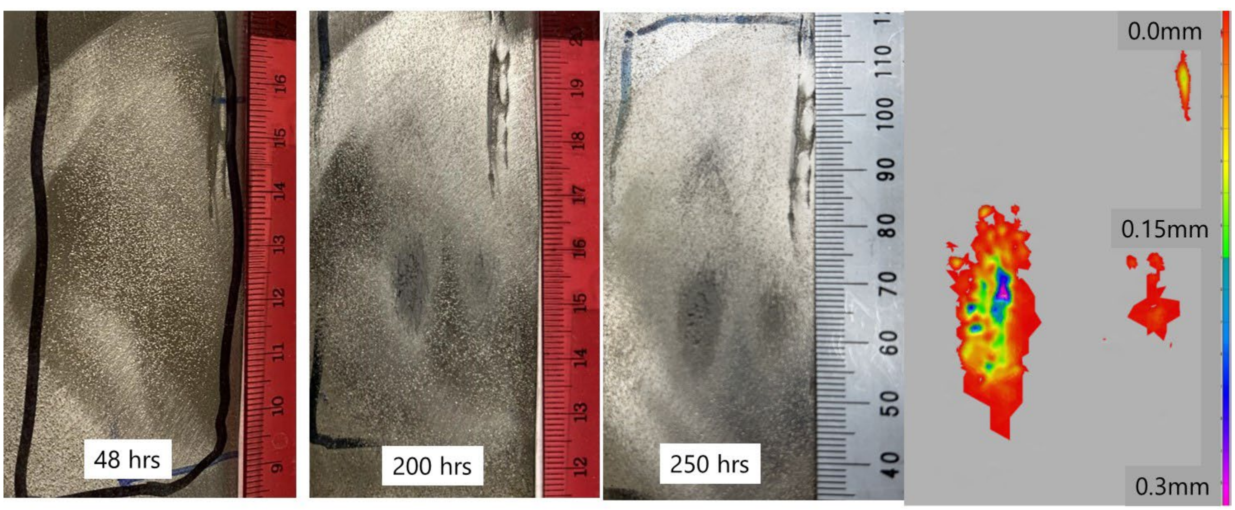

Figure 18.—Type 308/309 stainless steel weld overlay long-term cavitation testing results. The image to the right was developed from the laser scanner to show the volume and depth loss at 250 hrs. Ruler tick marks are in millimeters.

4.4.2 Cavitec

Cavitec had no material loss identified using the laser scanner. However, cracks developed in the impact and cavitation zones, shown in Figure 19. The laser scanner was unable to measure these visible changes. Cracking can be a significant problem, allowing electrolyte to the base material that could lead to galvanic and crevice corrosion cells forming.

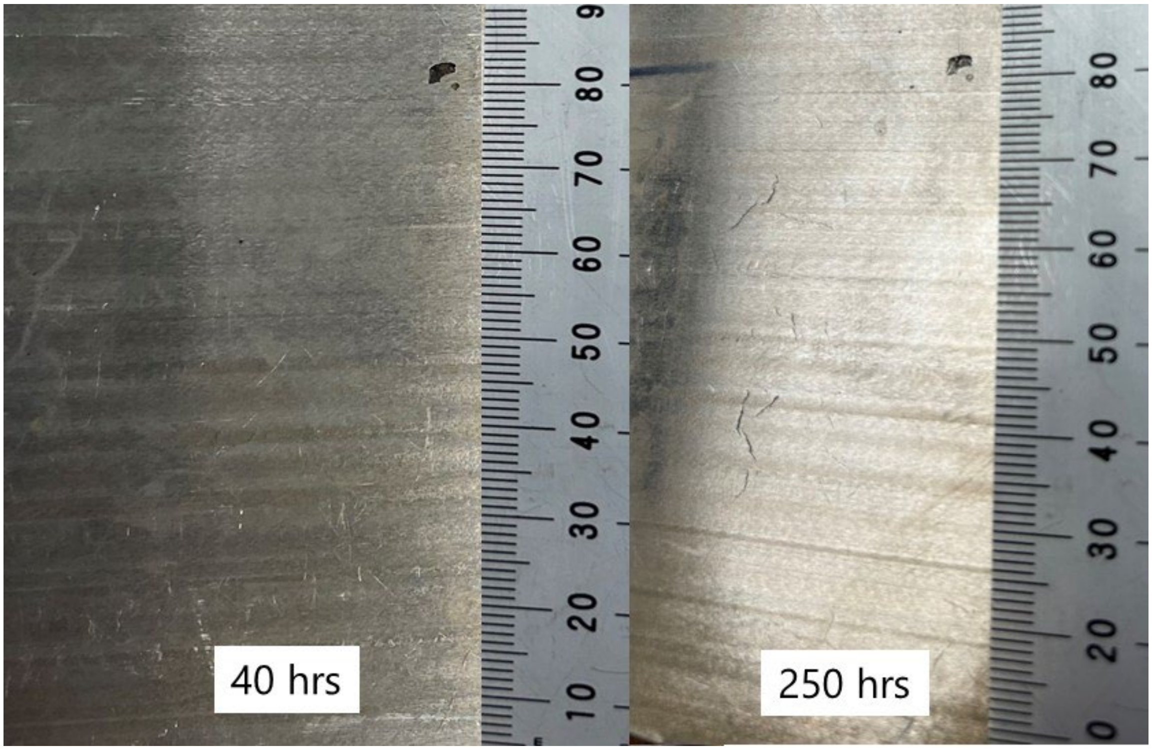

Figure 19.—Cavitec shown after 40 hours (hrs) and 250 hrs of long-term cavitation testing. Cracking is evident despite no measured metal loss. Ruler tick marks are in millimeters.

4.4.3 Cold Spray Applied Inconel 625 / Chromium Carbide 410-1

A blend of Inconel 625 and CRC-410-1 chromium carbide was applied by cold spray using three different application parameters and labelled as Cold Spray 2.1, Cold Spray 2.2, Cold Spray 2.3. All cold spray samples had no metal loss according to the laser scanner, but slight frosting was observed, shown in Figure 20. The images show less frosting compared to Type 316 stainless steel and are an improvement over the Type 308/309 stainless steel weld overlay. The cold spray results may warrant further investigation as a repair material for cavitation damage. Application techniques need further development so the process can be done in the field.

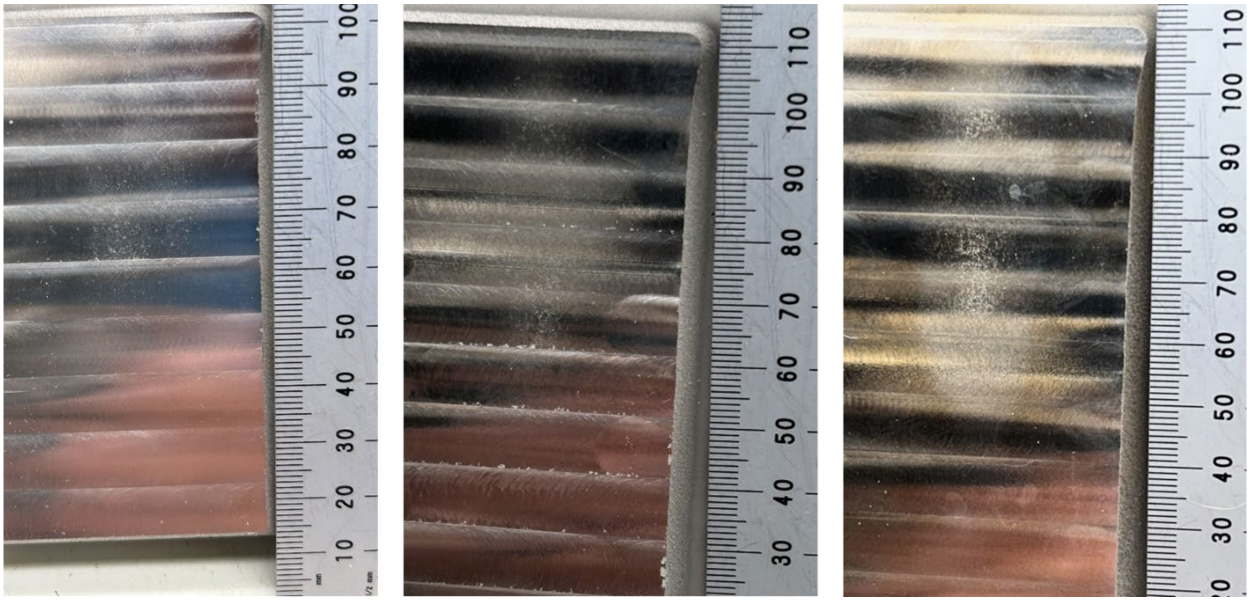

Figure 20.—Inconel 625/CRC-410-1 chromium carbide blend shown after 250 hours cavitation testing. Left: Cold Spray 2.1. Middle: Cold Spray 2.2. Right: Cold Spray 2.3. Ruler tick marks are in millimeters.

4.4.4 Polyurethane Elastomer 1

PE 1-1 lost 15.2 mm^3, while PE 1-2 lost 331.1 mm^3 after 250 hours. PE 1-1 had initial damage around 150 hours but did not fail to the substrate after 250 hours, as shown in Figure 21. The abrupt failure of PE 1-2 in the impact zone caused the epoxy primer to fail in a very short time, exposing the steel substrate. PE 1-2 failure depth was 2.2 mm with an approximate surface area of 150 mm^2 shown in Figure 22.

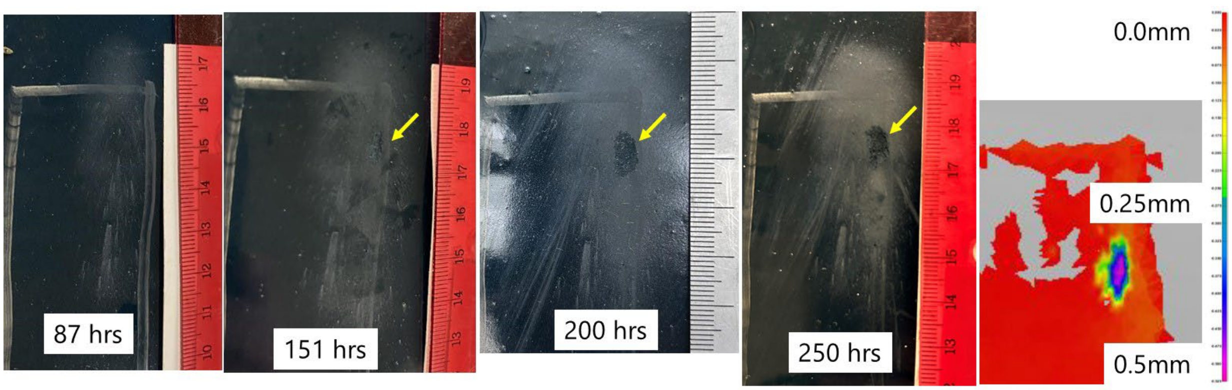

Figure 21.—PE 1-1 cavitation damage in long-term testing over four exposure times noted in hours (hrs). The image to the right was developed from the Laser scanner to show the volume and depth loss at 250 hrs. Ruler tick marks are in millimeters.

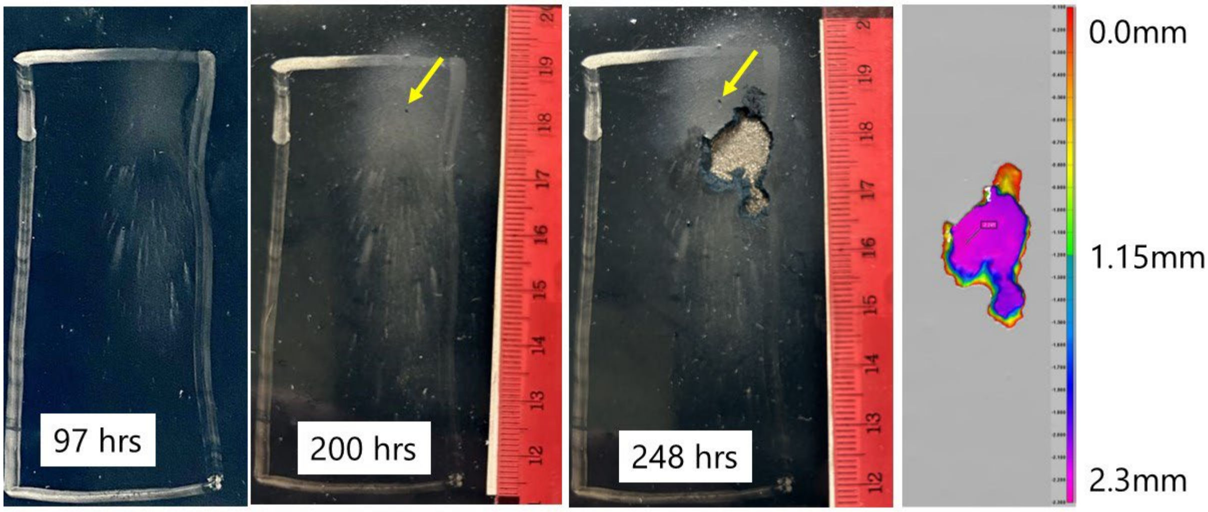

Figure 22.—PE 1-2 cavitation damage over three exposure times noted in hours (hrs). The image to the right was developed from the laser scanner to show the volume and depth loss at 248 hrs. Yellow arrows point to what appeared to be a point of failure initiation at 200 hrs but was still visible after failure at 248 hrs. Ruler tick marks are in millimeters.

4.4.5 Polyurethane Elastomer 2

PE 2-1 lost 5.1 mm^3, while PE 2-2 lost 43.7 mm^3 after 250 hours, as shown in Figure 23 and Figure 25, respectively. The damage was difficult to see visibly, but the Laser scanner was able to observe the microscopic changes in PE 2-1 and PE 2-2 over time as observed in Figure 24 and Figure 26, respectively. PE 2-1 had many small 1-mm diameter sized failures, that failed eventually to the substrate. This indicates excellent adhesion of the elastomer to the substrate. PE 2-2 had failure to the substrate in both the impact and cavitation zones, which may indicate this elastomer doesn't have as good of cavitation resistance compared to PE 1.

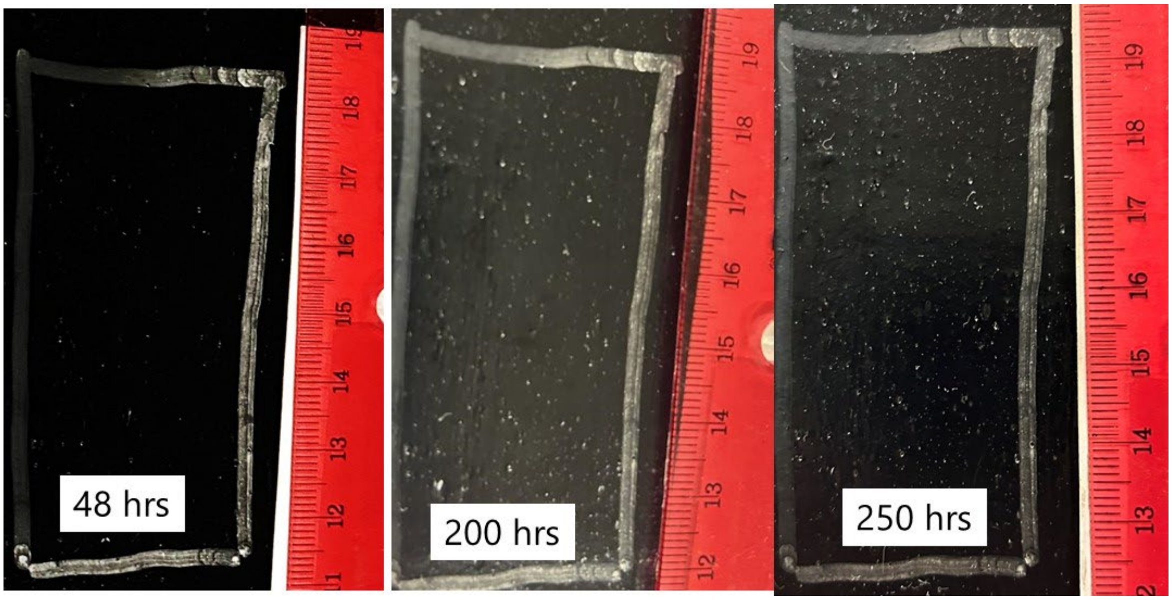

Figure 23.—PE 2-1 long-term cavitation, notice the damage is not visible. Ruler is in millimeters.

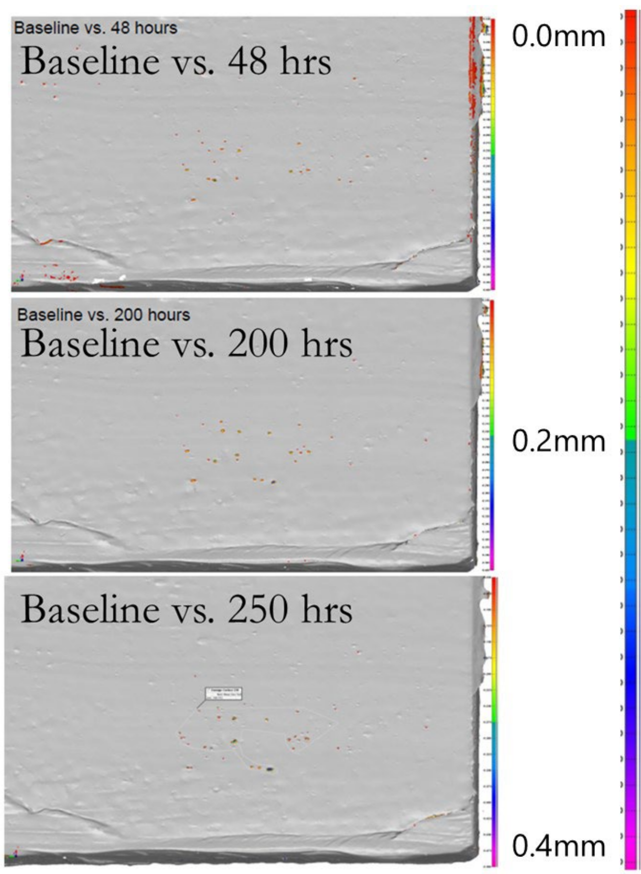

Figure 24.—PE 2-1 long-term cavitation using laser scanner to monitor the microscopic changes. Color bar scale is in millimeters.

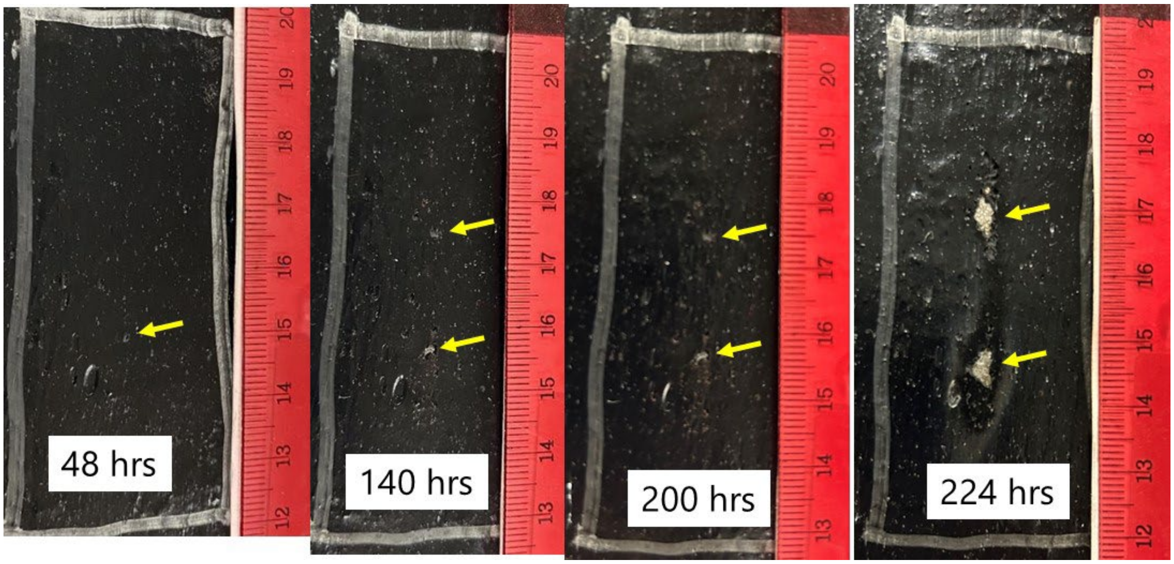

Figure 25.—PE 2-2 long-term cavitation testing over time, reported in hours (hrs). The top arrow shows the damage in the impact zone and the bottom arrow shows the damage in the pure cavitation zone. Ruler tick marks are in millimeters.

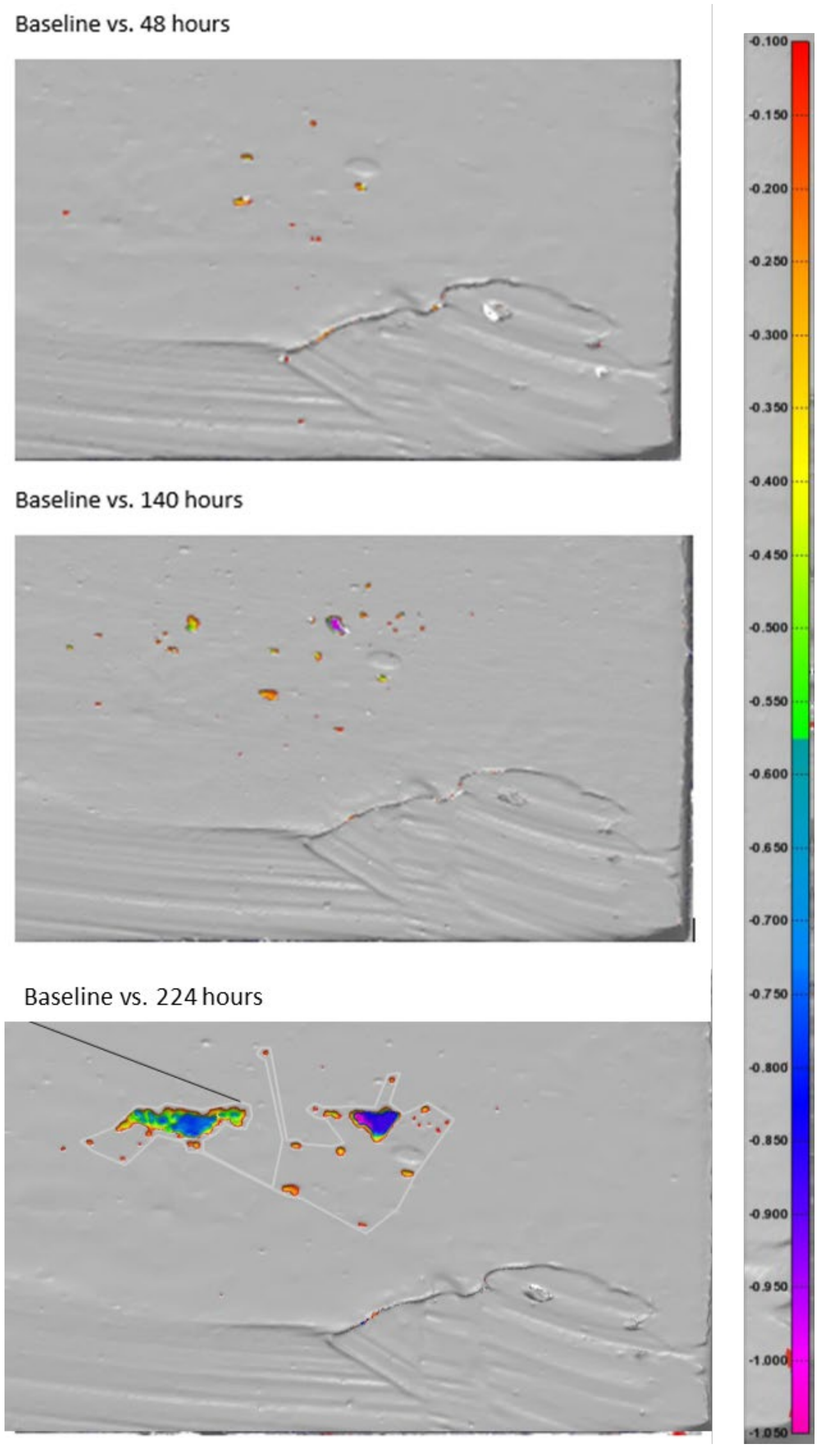

Figure 26.—PE 2-2 long-term cavitation using laser scanner to monitor the microscopic changes. Color bar scale is in millimeters.

The polyurethane elastomers appear to provide 150 hours without damaging, which is longer than initial damage for mild steel and Type 308/309 stainless steel weld overlay but failed relatively quickly after the initial damage area. For long-term performance in severe cavitation this would not be acceptable. The elastomers must prevent delamination once damaged, and this is achieved with adequate adhesion to keep the surface area of damage relatively small. The impact zone is a higher-intensity cavitation zone that may better-resemble a severe cavitation zone on hydropower components.

Field trials were deemed necessary to correlate laboratory test to field results. The elastomers could possibly provide short-term field performance in severe cavitation or provide improvements over the existing coatings used in mild or moderate cavitation. Two field trials were initiated in 2023 at Grand Coulee Dam and Flatiron Powerplant, as described in Section 5.

4.5 Effect of Cavitation Intensity

Further tests were performed with increasing cavitation intensities to determine PE 1 performance at higher cavitation intensities.

The test samples were 4-inch by 6-inch by 0.75-inch-thick mild steel coupons. One sample was prepared per test setting, starting with solvent cleaning to SSPC-SP1, followed by abrasive blast cleaning to SSPC-SP5 white metal using LG 25 steel grit to generate a 3.5 mil minimum surface profile [17] [18]. The PE 1 elastomer was applied in accordance with manufacturer's instructions. Table 2 shows the test parameters and the time to failure for PE 1 under three flow conditions. Thickness data is unavailable for this set.

Table 2.—Test Parameters and Time to Failure of PE 1 at Varying Flow Conditions

Flow rate (gpm)	Pressure (psi)	Cavitation Number*	Time to Failure (hours)
3.5	1450	0.0129	248
4	1900	0.0102	8.5
4.5	2450	0.0080	1.5

* Cavitation number decreases with increasing cavitation intensity.

PE 1 failed quickly with decreasing cavitation number, which relates inversely to cavitation intensity. This indicates that PE 1 and the other commercially available coatings tested in this research may not be able to withstand higher-intensity cavitation that can be encountered in field conditions. Further testing would be needed to determine material loss of PE, baseline, and other repair materials.

Since the submerged jet cavitation test procedure is new, it was previously unknown how the cavitation number correlates with field operating conditions. Researchers used the results from long-term testing detailed in Section 4.4 to determine which test parameters produced a "severe" cavitation environment, specifically basing this on the flow conditions that created visible cavitation damage on Type 308/309 stainless steel weld overlay. The associated test parameters resulted in a cavitation number of 0.0129. At this intensity, there was no metal loss on 316 stainless steel or cold spray samples, which confirms that the level remains below "extreme cavitation" conditions as defined in this report.

5. Field Testing

The research team deemed it necessary to conduct field trials to verify the laboratory findings of the research. The laboratory testing showed PE 1 and PE2 provide at least fifteen times longer cavitation resistance than PE7, which has performed well in draft tubes. Researchers therefore selected the PE 1 and PE 2 systems to validate this improved performance in severe cavitating environments in the field.

One field trial was performed at the Grand Coulee Dam Nathaniel “Nat” Washington Power Plant, on a large turbine runner in February 2023. The second field trial was performed at Flatiron Powerplant Unit 2, on a butterfly valve in March 2023. Full descriptions and results from the field trials are included in separate interim reports. Summarized outcomes and the interim report numbers are included in sections 5.1 and 5.2.

5.1 Grand Coulee Dam G21 Turbine Runner

Details, photographs, and results from the coating application and initial 1,000 hours of service inspection are included in Technical Memorandum No. 8540-2023-12 (Interim Report ST-2023-20024-02) and is attached as Appendix B.

The initial field results at Nathaniel “Nat” Washington Power Plant suggests similar results to the laboratory testing. Both systems experienced application challenges due to the high viscosity and short pot life. The PE 2 damage area was greater than PE 1, like the laboratory testing results. Both failed in less than 1,000 hours of operation in the most severe cavitation zone. The exact time of failure is unknown for PE 1 and PE 2, i.e., it could be fewer than 10 hours or more than 900 hours. PE 1 and PE 2 had no cavitation damage in the moderate and mild cavitation zones on the turbine runner.

5.2 Flatiron Power Plant Unit 2 Butterfly Valve

Details and photographs from the coating application are included in Technical Memorandum No. 8540-2023-34 (Interim Report ST-2023-20024-03) and is attached as Appendix C. Initial results are not available since the unit is in operation.

6. Future Work

The initial field test results help to confirm the laboratory method adequately represents cavitation conditions experienced on Reclamation structures. This helps to maximize the effectiveness of laboratory research and may allow for the advancement of polymer coating technologies, such as by testing candidate materials from partners or developing elastomers with increased performance in severe cavitation conditions. Future testing will need to confirm that increasing the cavitation intensity to shorten testing duration does not alter the field-validated cavitation processes or conditions. An accelerated approach could expedite development timelines.

Cold Spray Development

- PNNL is developing a cold spray process that can use nitrogen as the carrier gas, not helium. Future work will include development and qualification of inspection processes for this application.
- PNNL will perform a field application of cold spray at the U.S. Army Corps of Engineers (USACE) Little Goose Dam, located on the Snake River, next spring and fall.

Polyurethane Elastomers Experimental Formulation Development

- Polyurethane elastomer formulation has numerous component combinations that can be tailored to develop a more cavitation resistant material. This study has provided a good starting point to advance this technology.
- The Reclamation Materials and Corrosion Laboratory is continuing this work in the ongoing S&T Project ID 23009 to formulate rubberized polyurethane coatings. Initial results with several experimental formulations are already exceeding the laboratory test results of PE 1 and PE 2.
- USACE and Reclamation are collaborating to develop an improved cavitation resistant coating system using Military Specification epoxy primers, compatible adhesive, and experimentally developed elastomer. The envisioned applications are cavitation and erosion resistance using brush, roller, or spray. The currently available PE 1 and PE 2 materials are high viscosity and limited to brush and trowel application.
- Further testing could establish cavitation volume loss rates and variability for each material using the laser scanner and/or optical surface profilometer. Additionally, Type 304 stainless steel should be added to the list of baseline metals.
- Further testing would be needed to confirm if a minimum and maximum coating thickness is needed for elastomers to absorb the cavitation energy. The development of sprayable coatings will improve the ability to carry out this study due to more uniform film thicknesses and better control between replicates.

7. Conclusions

The research evaluated 5 metallic and 22 polymer coating materials using a laboratory cavitation testing method. The test apparatus applied severe cavitation to the samples in the impact zone with 1450 pounds per square inch pressure, 3.5 gallons per minute flow rate, and a cavitation number of 0.013. The objective of the research was to identify materials that can reduce cavitation and corrosion damage on Reclamation turbine runners and similar equipment. If found, this could reduce maintenance costs and extend maintenance cycles for cavitation repairs.

Laboratory cavitation testing found that epoxy and many polyurethane coatings have poor cavitation resistance. Only two elastomers, PE 1 and PE 2, showed adequate cavitation resistance to be selected for further evaluation. Follow-up laboratory testing showed these materials have good repairability, with abrasive blast cleaning required to prevent delamination. For initial findings, PE 1 required a minimum of 28 mils and PE 2 required a minimum of 21 mils to achieve cavitation resistance.

Other laboratory and field trial conclusions are as follow:

- For comparison with other materials, testing of baseline metals found that:
    - Type 316 stainless steel had no measurable metal loss after 250 hours but had light frosting.
    - Type A36 mild steel showed a pit form at 16 hours and had 180 mm^3 of material loss after 250 hours.
    - Type 308/309 stainless steel weld overlay began forming a pit at 40 hours and had 6 mm^3 of material loss after 250 hours.
- Cavitec provided no metal loss in 250 hours but cracked in the cavitation and impact zone. In a field setting, this type of damage could provide an electrolytic pathway to the substrate to cause galvanic and crevice corrosion and significantly lower service life.
- A blend of Inconel 425 and CRC-410-1 chromium carbide powders applied by cold spray with three different application parameters provided no metal loss after 250 hours and exhibited less frosting than Type 316 stainless steel. Cold spray performance was superior to the Type 308/309 stainless steel weld overlay.
- PE 1 and PE 2 had better cavitation resistance properties than the other coating materials tested and began showing damage in the pure cavitation zone at 150 hours with two samples failing to the substrate before 250 hours. In severe cavitation conditions, i.e., the impact zone, these two elastomers had no measurable damage for 100–150 hours before failing. The laboratory test results suggest the materials may provide good field performance in mild and moderate cavitation conditions.
- Initial field trials at Nathaniel "Nat" Washington Power Plant Unit G21 turbine runner resulted in the PE 1 and PE 2 elastomers failing within 1,000 hours of operation in the most severe cavitation zone of the suction side of the blade (see report in Appendix A). PE 1 and PE 2 resist moderate cavitation and could reduce galvanic corrosion between 308/309 stainless steel and mild steel. The field trial will determine the extent to which these materials reduce cavitation damage and corrosion.

Supporting Data Sets

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

- File path: T:\Jobs\DO_NonFeature\Science and Technology\2015-PRG-Cavitation Coatings
- Point of Contact: Allen Skaja, mailto:askaja@usbr.gov, 303-445-2396
- Short description of the data: Files primarily include email correspondences, Excel spreadsheets, photographs, Word documents, PowerPoint, and PDF's.
- Keywords: cavitation resistance, severe cavitation, ceramic epoxies, polyurethane elastomers
- Approximate total size of all files: 2664 Files, 698 Folders, 20.6 GB

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Appendix A— AMPP Conference Paper

Investigation of Polymeric Elastomers for Cavitation and Erosion Resistance

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ABSTRACT

Damage caused by cavitation and erosion is observed on hydro-turbines, pumps, pipes, gates, draft tubes, and outlet conduits. Mitigating the effects of this degradation on metallic hydraulic steel structures will reduce downtime and costly repairs. Traditionally, stainless steel weld overlays are used for cavitation repairs on these structures. Welding stainless to mild steel creates a galvanic corrosion cell in immersion conditions, which can cause delamination of the stainless steel and subsequent loss of cavitation protection. Cavitation resistant coatings could be used in combination with stainless steel weld overlays to eliminate the galvanic corrosion cell, thus providing protection and extending the service life of the repairs. This paper investigates the cavitation resistance and material properties of polymeric elastomer coatings. Several elastomers were selected for testing based on their mechanical properties such as percent elongation, tensile strength, tear resistance, and Shore hardness. Findings include the results of laboratory testing of cavitation resistant coatings. Elastomers are shown to provide better cavitation and erosion resistance than ceramic filled epoxies.

Key words: cavitation, coatings, erosion, corrosion

INTRODUCTION

Cavitation occurs in localized areas where there is a pressure drop across a structure; the water goes through a phase transition and forms water vapor. These vapor bubbles implode, resulting in high velocity micro-jets which impact adjacent surfaces. These impacts release shockwaves of energy, which cause microscopic particles of the surface material to flake off.[1] Repeated micro-jet impact causes microfractures in the affected surfaces and leads to pitting. Damage caused by cavitation is commonly observed on hydro-turbines, pumps, pipes, gates, draft tubes, and outlet conduits.

The Bureau of Reclamation's primary method for mitigating cavitation uses overlays of grades 308 and 309 stainless steel welded directly over mild steel.[2] The interface between the mild and stainless steel in water creates a galvanic corrosion cell. Coatings can be applied to reduce the galvanic corrosion cell, but cavitation damages epoxy-type coatings within a few hours of operation, exposing the stainless/mild steel interface. The progression of galvanic corrosion between the two metals eventually delaminates the overlay material. Once disbondment occurs, cavitation begins degrading the exposed mild steel.[2] The ideal coating for this application would resist cavitation for several years.

Figure 1: Image of a stainless-steel weld overlay failure in a draft tube. Galvanic corrosion and cavitation damage is observed in the mild steel.

This research investigated cavitation resistance of polymeric coatings to reduce the galvanic corrosion cell and extend the life of the stainless steel weld overlay repair for a dual protection method. Prior research in the 1960's investigated epoxy, ceramic-filled epoxy, steel-filled epoxy, flexible epoxy, polysulfide rubber, vinyl, polyurethane, natural rubber, and neoprene coatings to resist cavitation.[3-5] The polysulfide rubber and neoprene showed the most cavitation resistance in laboratory testing. In field testing, however, these materials exhibited delamination issues in high velocity water. Additional research conducted between 1958 to 1984 reported that neoprene not only demonstrated cavitation resistance but was also an excellent material for long-term erosion resistance.[7-14]

USACE research evaluated metallized coatings, ceramic-filled epoxy, and polyurethane elastomer coatings.[6] It was determined some ceramic-filled epoxy coatings and metallized coatings could be used in mild cavitation environments on a temporary basis.[6] The elastomers suffered from delamination but provided superior cavitation resistance and should be further evaluated, according to USACE recommendations.[6]

Data gathered from prior research indicates elastomers provide the best erosion and cavitation resistance.[4,13] The challenge is to achieve adequate adhesion of the coating to the steel substrate. Emerging technologies are overcoming adhesion issues while maintaining excellent cavitation and erosion resistance.[15] This research evaluated several ceramic-filled epoxy materials and elastomeric coatings to determine the best approach for field trials in moderate to severe cavitation and erosion environments.

EXPERIMENTAL PROCEDURE

Materials

The cavitation test samples were 10 cm (4 in) by 15 cm (6 in) by 1.9 cm (3/4 in) mild steel, at three replicates per system. The erosion test samples were 28 cm (11 in) diameter discs by 0.32 cm (1/8 in) mild steel, at two replicates per system.

All samples were prepared by solvent cleaning to SSPC-SP1, followed by abrasive blasting to SSPC-SP5 white metal using LG 25 steel grit to generate a 76 micron (3.5 mil) minimum surface profile.[16,17]

Test coatings were selected based on literature research, materials presently used to mitigate cavitation, and new technologies designed for cavitation and erosion resistance. The materials selected were divided into two categories: ceramic-filled epoxy and polyurethane elastomers. The materials were directly compared to USACE coating System No. 5-E-Z (zinc-rich vinyl). Five ceramic-filled epoxy coatings were evaluated and compared to five elastomeric polyurethanes. The coatings were applied in accordance with manufacturer's instructions. All samples were preconditioned for two weeks in water immersion prior to testing to ensure water absorption was at equilibrium.

Cavitation Test Method

The testing apparatus consists of a 7.5 kilowatt (10 horsepower) pump, hoses, a submerged jet with 0-degree, 0.17 mm (0.0065 in) diameter nozzle, a sample holder, and a 454 liters (120 gallon) water tank with a clear viewing window. Samples were installed on a sample holder at a 30 degree angle from the nozzle.[18,19] The angle allows the cavitation cloud to flow down the sample, as shown in Figure 2, 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). The nozzle was placed at a 6.4 cm (2.5 in) standoff distance from the sample. The pressure and flow rates were monitored by flow meters, pressure transducers, and Daisylab™ software. Testing parameters were set to respective flow rate and pressure of 13 liters per minute (3.5 gallons per minute) and 10 MPa ± 0.17 MPa (1450 ± 25 psi). Nozzle calibration was performed prior to testing. Atmospheric pressure and water temperatures are recorded daily during each test.

™ Trade name

There are two zones of damage on the samples, as shown in Figure 2. The impact zone exhibits degradation from direct jet impingement pressure and velocity, along with damage from cavitation. The pure cavitation zone is where bubble implosion occurs as the vapor cloud travels down the sample. The location of the pure cavitation zone was recorded for each sample.

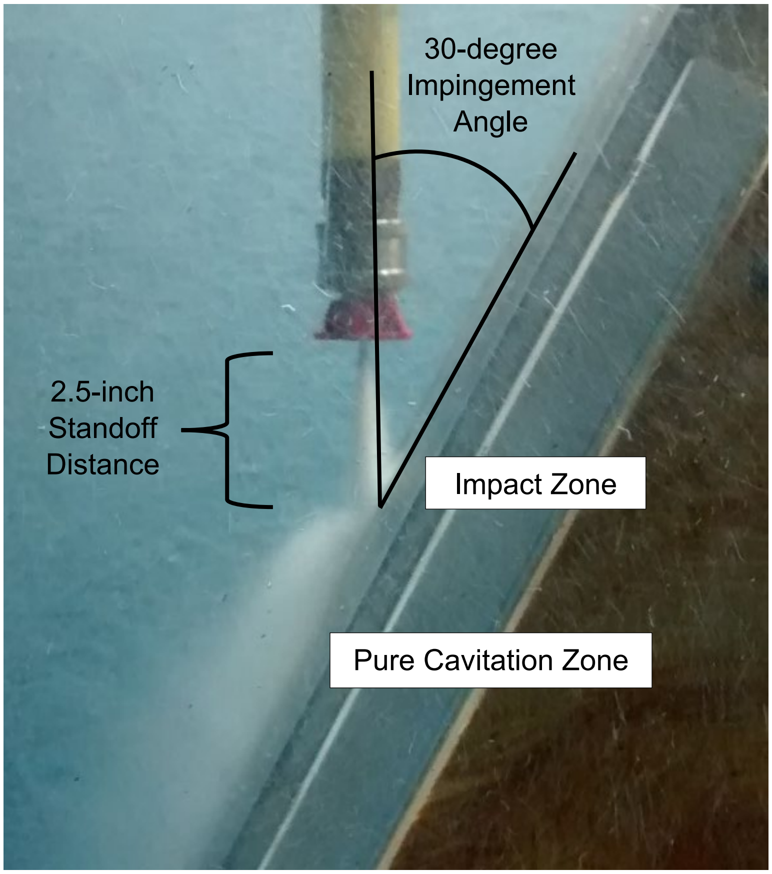

Figure 2: Submerged jet cavitation showing the sample angle with the cavitation travelling down the sample, along with the location of the two defining zones of damage.

Plates of mild steel, grade 316L stainless steel, and erosion resistant (ER) 308/309 stainless steel weld overlay were selected as baseline materials for calibration and verification of the desired extent of damage. The flow conditions were adjusted to a condition which produced light frosting damage on stainless steel 316L and moderate pitting to mild steel at 40 hours, shown in Figure 3. Exposed to these flow conditions, 308/309 stainless steel weld overlay exhibited minimal pitting after a 40-hour period of exposure, as shown in Figure 4. The same flow conditions caused mild steel to show cavitation damage at 16 hours and measurable damage at 40 hours, as shown in Figure 5. These visual indicators of damage on the baseline materials are consistent with similar types of visual degradation observed in field conditions.

Samples were tested for 8-hour periods and checked for damage at 1- to 2-hour intervals throughout the day. Once coating damage to the substrate occurred, the sample was deemed to have failed, and it was removed from testing. Samples with no visible damage remained in testing for up to a total of 40 hours. All samples that passed 40 hours of testing are considered candidates for longer testing durations and field trials.

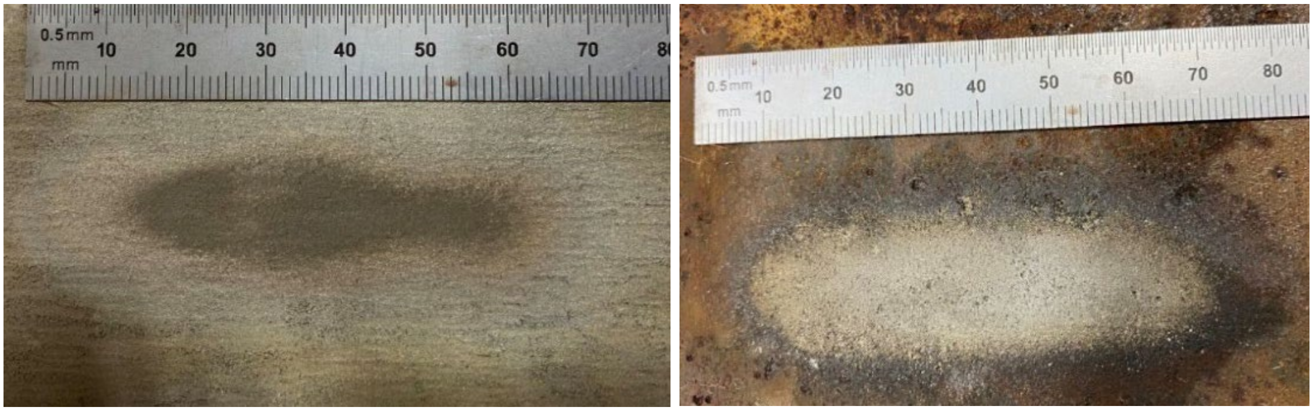

Figure 3: Stainless steel 316L (left) and mild steel (right) after 40 hours exposure to submerged jet cavitation apparatus. Notice pitting caused by cavitation in the mild steel.

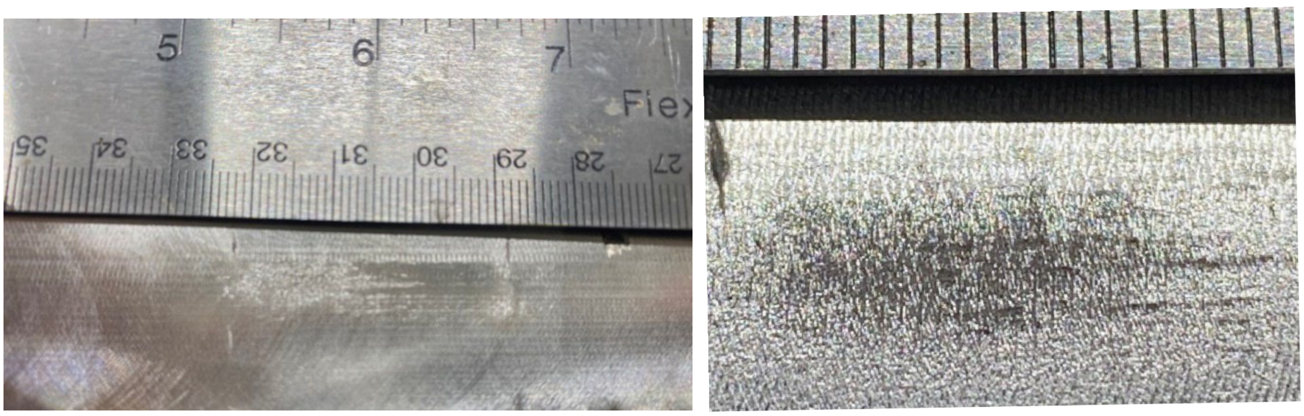

Figure 4: Photo of ER308/309 stainless steel weld overlay after 40 hours exposure to cavitating jet apparatus. The damaged area is significantly less than mild steel.

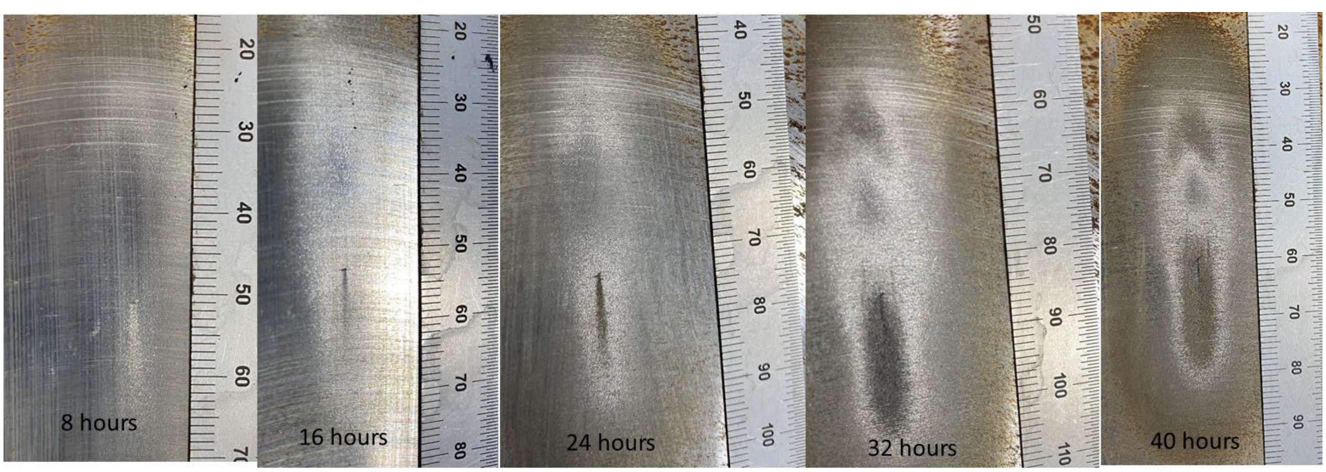

Figure 5: Baseline testing of mild steel and progression of cavitation damage.

Traditional cavitation testing on metals uses mass loss as a measure of cavitation progression, which is an ineffective method for evaluating polymeric coatings on metallic substrates. Polymeric coatings have lower density and have more difficult to measure mass loss compared to metals. For example, the mass loss from damaged coatings are difficult to resolve using a standard lab-precision scale due to the large difference in mass of the metal substrate. Another issue with measuring mass loss is that some coatings abruptly fail in a short period; coating tears that remain partially attached to the substrate show no measurable loss of mass. Therefore, time to failure was used to determine a coating material's cavitation resistance, with failure defined as substrate exposure.

Erosion Test Method

The research team developed an erosion test procedure to evaluate coating erosion resistance by modifying ASTM[(1)] C1138 Standard Test Method for Abrasion Resistance of Concrete (Underwater Method).[20,21] The modification used #16 sieved aluminum oxide to erode coatings instead of stainless steel ball bearings. Samples were fastened to the base of a cylindrical tank with dimensions of 41 cm (16 in) height and 29.2 cm (11.5 in) inner diameter, which is filled with approximately 20 liters of water and 1000 grams of sieved aluminum oxide. A jiffy paint mixer paddle positioned 85 mm (3.3 in) above the bottom of the test tank was used to agitate the aluminum oxide slurry. A vertically oriented motor with a speed of 1140 revolutions per minute spins the paddle for a test duration of 96 hours.

Samples were weighed every 24 hours and compared to a control sample to correct for water absorption. The test and control samples were removed from the tank and water bath, respectively, rinsed, and dried with rags before being weighed. The weight loss was calculated as the weight change of the test samples less the mass change of the control sample. The average mass loss and standard deviation were then normalized by the density of the coating to obtain the volume loss. The volume loss was divided by the surface area of the samples and multiplied by conversion factors to obtain thickness loss per hour of testing.

RESULTS AND DISCUSSION

Cavitation Resistance

Researchers evaluated different coatings marketed as cavitation or slurry erosion resistant materials. Coating manufacturers typically recommend ceramic-filled epoxy or elastomeric polymers for severe service environments, such as cavitation and erosion. Figure 6 shows the results of the cavitation resistant materials listing each material type and corresponding time to failure. The zinc-rich vinyl system failed within 2 hours in the cavitation zone. All five ceramic-filled epoxy coatings failed within 8 hours of testing, primarily in the pure cavitation zone, with some damage in the jet impact zone. Elastomeric polyurethane coatings 1, 2, and 5 passed the 40-hour criterion. Polyurethane elastomer 1 had a slight change in gloss after 40 hours of cavitation testing whereas polyurethane elastomer 2 had no change in appearance. Elastomeric polyurethane coatings 3 and 4 failed in the impact zone at 6 hours. Elastomer 5 had some damage but had not failed in 40 hours. The cavitation results show that the ceramic-filled epoxies have poor cavitation resistance and not all elastomeric polyurethanes perform equally in cavitation conditions.

The initial screening terminated the test at 40 hours to determine which coatings should be further investigated. Long-term testing of Polyurethane Elastomer 1 and 2 is underway and will be included in a subsequent publication.

[1] ASTM International (ASTM), 100 Barr Harbor Dr., West Conshohocken, PA 19428.

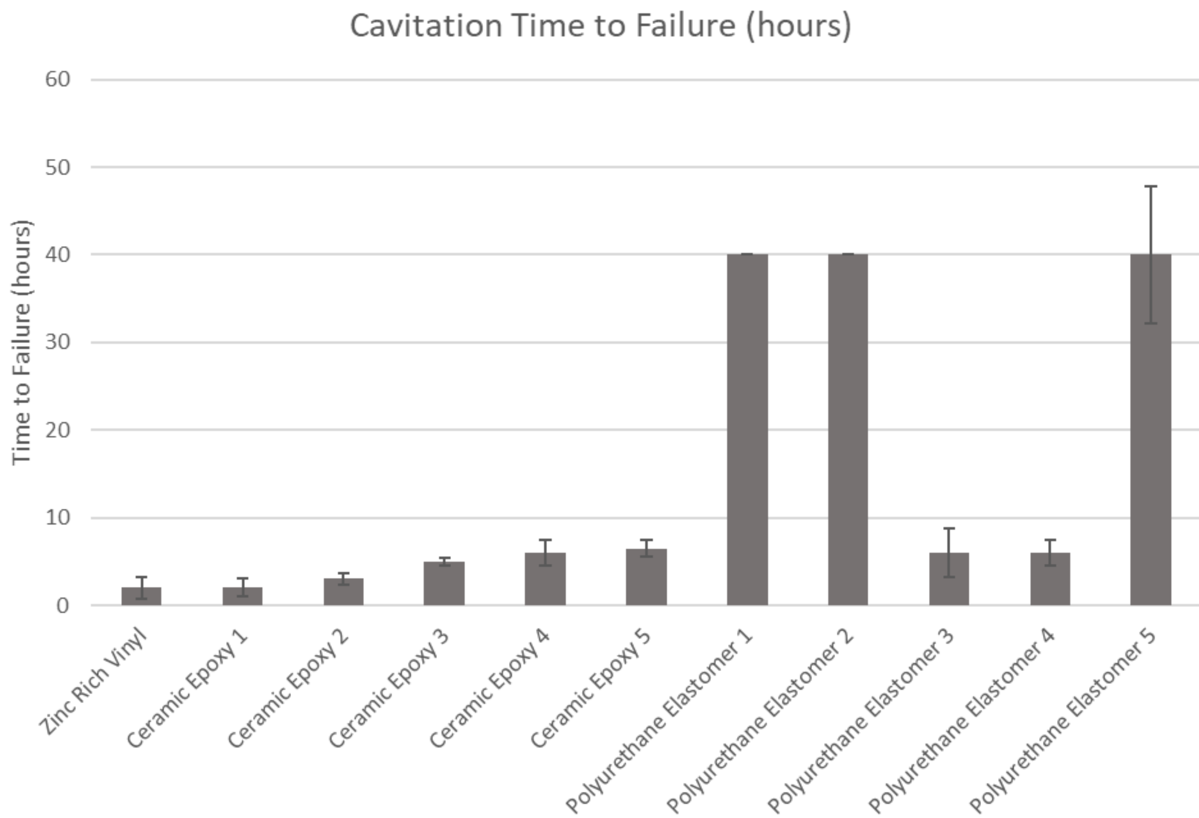

Figure 6. Cavitation test results for average time to failure to substrate. The ceramic epoxy systems and polyurethane elastomers 3 and 4 failed within six hours of testing compared to polyurethane elastomers 1, 2, and 5, which passed the 40-hour test. Elastomer 5 had some damage but didn't fail to substrate.

Cavitation resistance is determined by the material properties, but the material properties required to resist damage from cavitation are not fully understood. The manufacturers' published materials properties for polyurethane elastomers 1, 2, and 5 are listed in Table 1 and are not verified via in-house testing. It is reasonable to expect that higher tensile strength and tear resistance provide better cavitation resistance. Elongation must also be high enough for the coating to absorb the deformation caused by cavitation impact energy without succumbing to fatigue failure.[22] In addition, ample coating thickness is required to absorb the cavitating jet energy. Rebound resiliency (ability to resist damage) is another property which may play a role in cavitation resistance.[22] Rebound resiliency is not measured or reported by coating manufacturers, but it is often reported in the rubber tire industry. Rebound resiliency differs from elongation in that it represents a materials ability to recover after stress, whereas elongation includes the non-recoverable phase of a material.

Table 1. Material Properties of Polyurethane Elastomers 1, 2, and 5 – manufacturers' published materials properties

	Shore Hardness A	Tensile Str MPa (psi*)	Tear Str MPa (pli**)	Percent Elongation	Dry Film Thickness Applied mm (mils)
Polyurethane Elastomer 1	87	15.2 (2200)	2.6 (380)	530	1.27-1.52 (50-60)
Polyurethane Elastomer 2	87	24.1 (3500)	2.8 (400)	600	0.76-0.89 (30-35)
Polyurethane Elastomer 5	87	11.7 (1700)	2.1 (300)	300	0.76-0.89 (30-35)

*Pounds per square inch (psi)
**Pounds per linear inch (pli)

Polyurethane Elastomers 3 and 4 failed in the high intensity jet impact zone and might exceed the compression set or resilience of the material, meaning that the material does not recover to the original dimension after the compression caused by the cavitating jet. The result does not mean these coatings are not cavitation resistant but instead that the jet velocities and pressures exceed this yield value. Another possible explanation is that frictional heat generated in the cavitation process does not dissipate within the material, and the sample properties change as the temperature increases.[23]

The cavitation test procedure has not yet been correlated to actual field performance on infrastructure. Field trials on a turbine runner will begin in 2023 to determine if the lab test correlates to field performance. The baseline material testing results provided the anticipated outcomes regarding the order of time to failure for mild steel, 316L, and 308/309, indicating the laboratory test results are likely to correlate well with field performance.

Slurry Erosion Resistance

Slurry erosion results show the erosion rate of a material by measuring the weight loss, normalized with the cured coating density, and surface area of the test samples to obtain thickness loss per hour, shown in Figure 7. The rate of erosion is highest for the vinyl system, which is approximately 0.38 microns material loss per hour (μm/hr) The ceramic filled epoxy coatings range between 0.18 to 0.3 μm/hr. The polyurethane elastomers had lower erosion rates than the ceramic-filled epoxy and vinyl but were highly variable. The material loss of Polyurethane Elastomer 1 was 0.06 μm/hr, Polyurethane Elastomer 2 was 0.02 μm/hr, polyurethane elastomer 3 was 0.16 μm/hr, polyurethane elastomer 4 was 0.24 μm/hr, and polyurethane elastomer 5 was 0.12 μm/hr.

The theoretical service life of each material, shown in Figure 8, is determined by the coating thickness divided by the erosion rate. Vinyl is a low solids coating system. Building up the thickness would require approximately 20 coats to obtain a 1000 microns thick coating, which is impractical in the field. Instead, ceramic-filled epoxy coatings that are 100 percent solids and polyurethane elastomers can be used to build the thickness to achieve the desired service life. Polyurethane elastomers 1 and 2 theoretically can provide the longest service life against the erosion test.

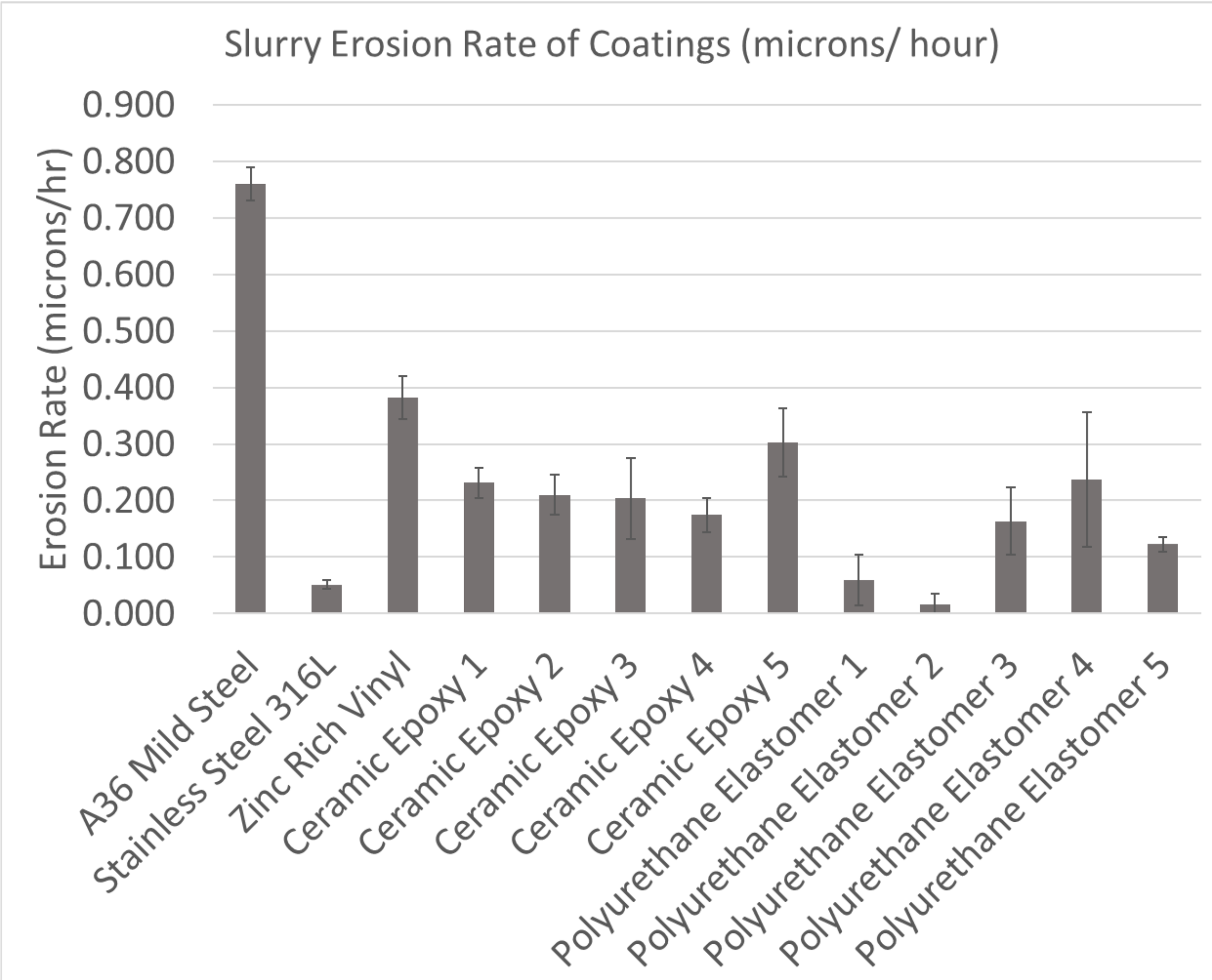

Figure 7. Slurry erosion rate of ceramic epoxy coatings compared to polyurethane elastomers.

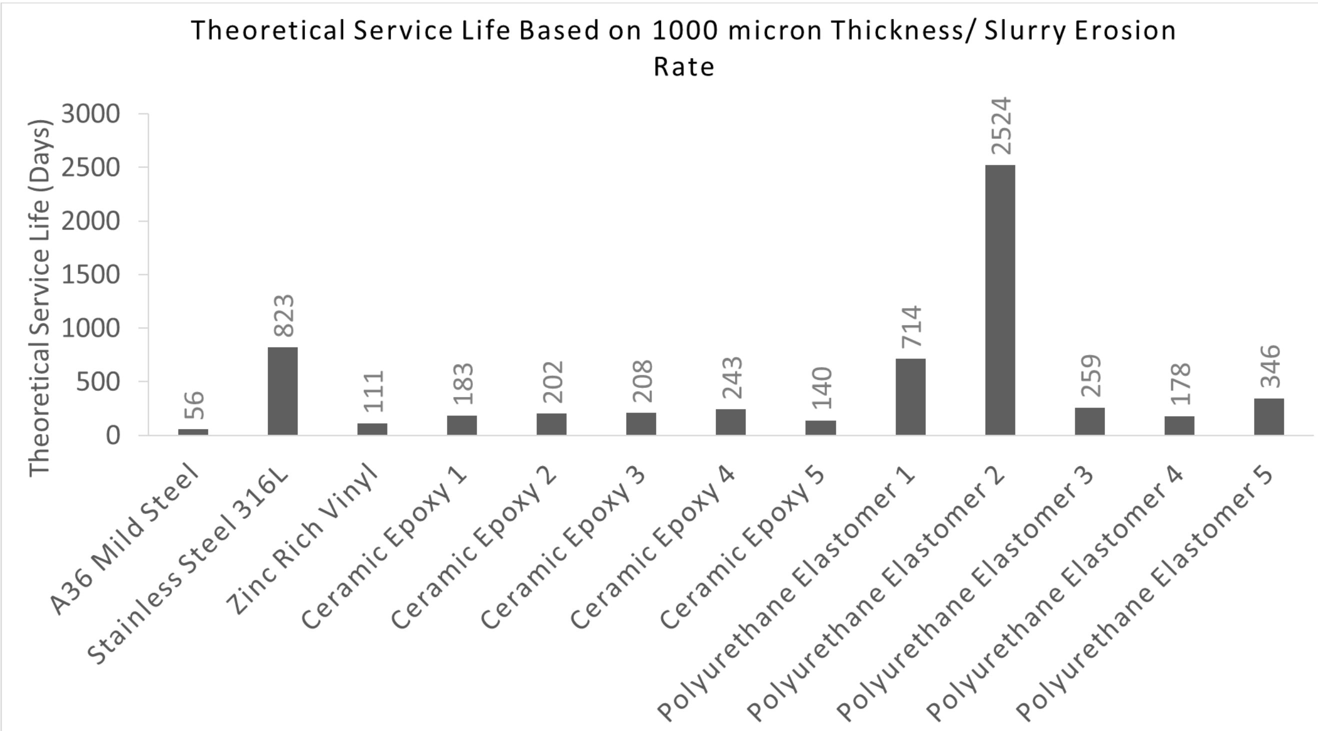

Figure 8. Theoretical service life for slurry erosion environments.

Polyurethane elastomers 1 and 2 had better cavitation and erosion resistance than other materials evaluated. According to the manufacturer's published data, these products had the highest elongation of all the materials evaluated, with available elongation data. Polyurethane 2 had slightly higher tensile strength, tear resistance and percent elongation compared to polyurethane 1. The slight improvement in cavitation and erosion resistance could be attributed to the increase in these materials properties. Future research could confirm correlation between cavitation and erosion resistance.

CONCLUSIONS

The research sought to identify a cavitation resistant coating that could be applied over a stainless steel weld overlay for dual protection from galvanic corrosion and enhanced cavitation resistance. Researchers tested several polyurethane elastomers, ceramic-filled epoxies and a zinc rich vinyl system to determine the best cavitation-resistant options. Experimental results have thus far shown that polyurethane elastomers provide the best cavitation and erosion resistance. The polyurethanes with high tensile strength, tear resistance, and elongation properties also had the highest cavitation and erosion resistance. Polyurethane elastomers 1 and 2 will be scaled up for field application to determine their in-situ performance and correlate the laboratory testing to field performance.

The next steps of this research are to:

1. Conduct long-term laboratory testing of polyurethane elastomers 1 and 2, with direct comparisons to stainless steel, mild steel, and ER308/309 stainless steel weld overlays.
2. Perform field trials are scheduled to determine if the polyurethane elastomers 1 and 2 laboratory performance translates to moderate to severe cavitation environments in the field.
3. Proceed with field scale up if field trials are successful
4. Correlate laboratory test parameters to the cavitation intensity observed on field infrastructure.

5. Try developing a mechanical properties model for cavitation resistance using polymeric elastomers.

DISCLAIMER

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

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This research was supported by the Science and Technology office of the Bureau of Reclamation under project number 20024. We also want to thank our intern, Ryan Williams, for contributing to this work. We also want to thank Stuart Croll, (Allen Skaja's former Ph.D. Advisor at North Dakota State University), for his interest and insightfulness into this project on trying to understand why some elastomers performed well.

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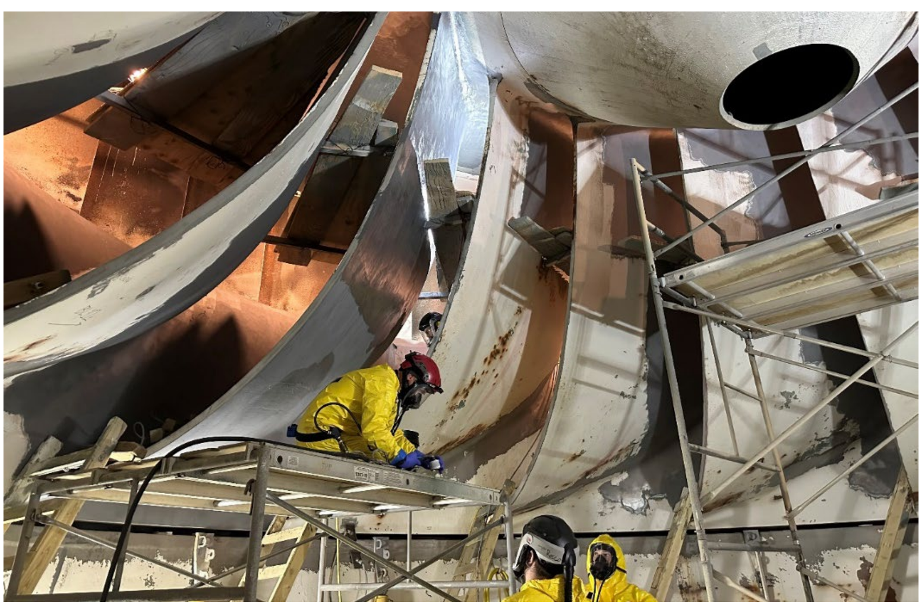
Appendix B— Grand Coulee Field Trial

Nathaniel “Nat” Washington Power Plant G21 Turbine Runner Cavitation Resistant Coating Field Trial

Interim Report No. ST-2023-20024-02
Technical Memorandum No. 8540-2023-12

Columbia Basin Project, Washington
Columbia-Pacific Northwest Region



U.S. Department of the Interior

December 20, 2023

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<tr><td colspan="6">14. ABSTRACT
Cavitation resistant coatings have been used in mild cavitation conditions with mixed results, and rarely lasted more than a few years before needing repair. Laboratory testing identified two commercial polyurethane elastomers with better cavitation resistance than prior coatings used in draft tubes for cavitation resistance. These two elastomers, PE1 and PE2, were selected for field trials on Nathaniel “Nat” Washington Power Plant Unit G21 turbine runner, a severe cavitation environment in which stainless steel weld overlays require repairs of pitting damage on a three-year rotation. The goal of the field trial is to determine if the elastomers can reduce stainless steel cavitation in a severe cavitation environment to lengthen the repair cycle and reduce cost. This interim report documents the surface preparation and coating of Blades 7 and 13 with PE2 and PE1, respectively.</td></tr>
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Nathaniel "Nat" Washington Power Plant G21 Turbine Runner Cavitation Resistant Coating Field Trial

Interim Report No. ST-2023-20024-02
Technical Memorandum No. 8540-2023-12

Columbia Basin Project, Washington
Columbia-Pacific Northwest Region

prepared by

Technical Service Center
Materials and Corrosion Laboratory Group
Allen Skaja, Ph.D. Protective Coatings Specialist

Cover photograph: The team applies adhesive to a turbine runner blade.

Peer Review

Bureau of Reclamation
Technical Service Center
Materials and Corrosion Laboratory Group

Interim Report No. ST-2023-20024-02
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Nathaniel "Nat" Washington Power Plant G21 Turbine Runner Cavitation Resistant Coatings Field Trial

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Contents

Executive Summary

Cavitation damages hydro-turbines, pumps, pipes, gates, draft tubes, and outlet conduits, resulting in expensive downtime and costly repairs across Reclamation. Stainless steel weld overlays are traditionally used for cavitation repairs on affected structures, which are usually mild steel construction. Cavitation resistant coatings have been used in mild cavitation conditions with mixed results, and rarely lasted more than a few years before needing repair. Laboratory testing of two polyurethane elastomers (which have rubber-like properties) demonstrated superior cavitation resistance compared to prior coatings used in cavitating environments. The laboratory test data indicate these two commercial coating materials, PE1 and PE2, may provide protection in severe cavitating environments when compared to more traditional stainless steel weld overlays. A field trial was deemed necessary to confirm the cavitation resistance of these materials in operational cavitating environments.

Grand Coulee Dam (GCD) supervisors agreed to perform a field trial at the Nathaniel "Nat" Washington Power Plant on Unit G21 turbine runner, which was undergoing cavitation repair maintenance during the week of February 6, 2023. PE2 and PE1 were applied to the downstream sides of Blades 7 and 13, respectively, in Unit G21. The remaining supply of PE2 was used to line the downstream crotch area of the cavitation zone on Blade 8 on March 15, 2023, evaluating a cavitation resistant coating over the corrosion resistant epoxy coating. The Unit G21 return to service date was May 26, 2023, i.e., the field start date for exposure to the severe cavitating environment.

In mid-August, the Unit G21 transformer experienced a failure, and there was a stop in power generation. On October 18, 2023, Grand Coulee staff inspected the PE1 and PE2 cavitation resistant coatings after approximately 1,000 hours of operation. The inspection showed coating damage to PE1 in the most severe cavitation zone on the downstream side of Blade 13, spanning approximately 1 square foot. Approximately 10 square feet of coating damage was noted on PE2 on Blade 7, where the coating was disbonded for five feet along the leading edge. Blade 8 was accidentally omitted from the inspection, but the photos provided indicate complete coating disbondment of PE2 on the leading edge. This indicates PE1 and PE2 experience some cavitation damage in the severe cavitation zone within 1000 hours of operation. Evaluation in other field trials, including moderate cavitation environments, is needed to determine if the coatings prevent cavitation damage for longer operating periods and mitigate the galvanic corrosion cell. Additionally, a longer evaluation period at Unit G21 will determine if PE1 and PE2 provide an advantage in reducing the extent of cavitation damage during the three-year rotation cycle.

Recommendations for Grand Coulee Nathaniel "Nat" Washington Power Plant:
GCD should record the total number of hours Unit G21 operates, record the operating conditions, and conduct periodic inspections. Visual inspection and detailed photos should be taken of the three blades with PE1 and PE2 field trials and directly compared to the same locations on other blades using conventional repair procedures. Provide a scale reference in each image and submit information to the TSC project lead, Allen Skaja (askaja@usbr.gov).

Respirators or powered air purifying respirators (PAPRs) with air purifying cartridges could be worn, removing the need for supplied air lines for future applications of these systems by brush and trowel applications. Chemical-resistant clothing and gloves should always be worn to limit dermal exposure during application.

1. Background

Cavitation damages hydro-turbines, pumps, pipes, gates, draft tubes, and outlet conduits, resulting in expensive downtime and costly repairs across Reclamation. Stainless steel weld overlays are traditionally used for cavitation repairs on affected structures, which are usually mild steel construction. Welding stainless steel to mild steel creates a galvanic corrosion cell in immersion conditions and limits the lifetime of the stainless steel repair, limiting the duration of cavitation protection. Cavitation resistant coatings could be used in combination with stainless steel weld overlays to eliminate the galvanic corrosion cell, thus providing protection and extending the service life of the repairs.

The Research and Development Office's Science and Technology Program funded project number 20024, Field Repairable Materials and Techniques for Cavitation Damage, a laboratory research effort which evaluated 24 commercial coating materials for cavitation resistance [1]. The tests subjected the candidate materials to high-velocity impinging water conditions, and compared the results to type 316 stainless steel, ASTM A36 mild steel, and type 308/309 stainless steel welds overlaid on mild steel. Two polyurethane elastomers (materials with rubber-like properties) showed excellent cavitation resistance in laboratory testing, performing comparable to 308/309 stainless steel weld overlays. The other 22 coating materials exhibited damage within eight hours of the lab testing conditions, compared to 150–250 hours for the two polyurethane elastomers. Table 1 provides typical observations for the varying severity of cavitation intensity.

Table 1.—Cavitation severity levels defined for this research based on the damage level observed in traditional polymer coatings, mild steel, Type 308/309, and 316-series stainless steels after 200 hours of laboratory testing or an estimated 10,000-hour exposure in the field.

Cavitation Intensity	Traditional Polymer Coatings	Mild Steel	Type 308/309 Stainless Steel	Type 316 Stainless Steel
Mild	Volume loss and some complete removal	Light frosting/ minor metal loss	No damage	No Damage
Moderate	Complete removal	Moderate metal loss	Light frosting	No Damage
Severe	Complete Removal	Severe metal loss	Moderate metal loss	Light frosting
Extreme	Complete Removal	Severe metal loss	Severe metal loss	Moderate metal loss

The laboratory results suggest the two top performing polyurethane elastomers, PE1 and PE2, might perform well in moderate or severe cavitation field environments. Field trials were necessary to determine these materials' capabilities and limitations.

A solvent-borne epoxy coating has been the standard coating for the turbine runners at Nathaniel "Nat" Washington Power Plant for more than 20 years. The solvent-borne epoxy coating is not damaged by cavitation on approximately 80 percent (%) of the runner.

2. Field Trial Details

Grand Coulee Dam (GCD) supervisors agreed to perform a field trial at the Nathaniel "Nat" Washington Power Plant on Unit G21 turbine runner, which was undergoing cavitation repair maintenance during the week of February 6, 2023. PE1 and PE2 were applied to the downstream (suction) sides of Blades 7 and 13 in Unit G21. The remaining supply of PE2 was used to coat the cavitation zone on Blade 8 on March 15, 2023, giving it an additional layer of cavitation protection over the corrosion resistant epoxy previously applied.

2.1 Surface Preparation

The turbine runner of Unit G21 was abrasive blast cleaned to white metal, NACE 1/SSPC-SP5, using 16-grit Kleen Blast® abrasive [2]. After cleaning, the surface profile averaged 3.7 mils (mil) on the mild steel areas and 3.6 mil on the stainless steel weld overlay. The manufacturers of

PE1 and PE2 specify a minimum 3.0-mil profile. The cleaned surface of the turbine runner is shown in Figure 1.

2.2 Primer Application

The painting team, consisting of staff from GCD and the Technical Service Center (TSC), applied a ceramic-filled epoxy primer to Blades 7 and 13 on February 4, 2023, using brushes and trowels to coat approximately 210-square foot (sq ft) on the suction side of the blades. Each 3-kilogram kit was applied to a 36-sq ft area with an average dry film thickness (DFT) of 16.6 mil, a maximum reading of 72.6 mil, and a minimum of 1.2 mil. The manufacturer recommended 15 mil thickness. The primer's high viscosity made it difficult to maintain a uniform thickness using brush and trowel application. The GCD staff expressed their preference for spray application because it provides more uniform results. Environmental conditions were not recorded during the primer application.

2.3 Sweep Blast of Primer

Using 16-grit Kleen Blast® abrasive, the primer was sweep blast cleaned to SSPC-SP7, which removed all gloss [3]. The measured surface profile averaged 5.2 mil, exceeding the manufacturer's 2-mil profile requirement. A higher profile in the primer surface could increase mechanical adhesion for the elastomer and decrease the chance of delamination. The sweep blasted primer surface is shown in Figure 2.

2.4 Blade 13 Adhesive and PE1 Application

The team completed the application of adhesive to Blade 13 between 9:30 a.m. and 11:00 a.m. on February 7. Environmental conditions were measured in degrees Fahrenheit (F) before the application and are documented in Table 2 and shown in Figure 3. A thin layer of adhesive was brush-applied to the roughened ceramic-filled epoxy surface. As seen in Figure 4, each employee wore full personal protective equipment (PPE) and isocyanate exposure monitoring equipment; see Section 4. Exposure Assessment During Field Trial for details.

Table 2.—Environmental Conditions Just Before Application of Adhesive to Blade 13

Environmental Condition	Measurement
Relative Humidity	43.3%
Ambient Air Temperature	59.5F
Steel Temperature (Ts)	55.9F
Dew Point Temperature (Td)	37.2F
Delta Ts-Td	18.7F

Environmental conditions were measured at approximately 1:00 p.m., just before applying PE1 to Blade 13. The measurements are listed in Table 3. The manufacturer advises that one kit of

PE1 covers 7.5 sq ft at 40 mil DFT. Before applying PE1, GCD staff prepared approximately 28 grids, 2.5 feet by 3 feet each, to mark the application areas for one kit. However, the team found that one kit covered less than a single grid due to the high viscosity of the mixed system.

Table 3.—Environmental Conditions Just Before Application of PE1 to Blade 13

Environmental Condition	Measurement
Relative Humidity	40.1%
Ambient Air Temperature	62.3F
Steel Temperature (Ts)	56.9F
Dew Point Temperature (Td)	37.8F
Delta Ts-Td	19.1F

PE1 is a two-component polyurethane with a 13-minute pot life. Each PE1 kit was mixed by hand for about three minutes, then troweled onto the adhesive coated surface. Application of PE1 to Blade 13 occurred between 2:00 p.m. and 5:30 p.m. As shown in Figure 5, each employee wore full PPE and isocyanate exposure monitoring equipment.

A visual inspection was performed the following day, February 8. Most of the newly coated area was fully cured, but some areas remained tacky, which prompted inspection of the used product containers. Some of the remaining material at the bottom of a mixing container was not solid, and a few Part B containers had 5–10 milliliters left in the bottom. This suggests some kits were not mixed with the full amount of Part B, resulting in improper mix ratios. Skaja advised the team to wait seven days to allow for complete curing and then conduct a sweep blast over the entire surface to find and remove incompletely cured areas, which would require spot repair following the manufacturer's instructions.

On February 10, the team performed holiday and DFT testing. Holiday testing found no defects in the coating. The coating thickness averaged 46.3 mil with a maximum of 79.3 mil and a minimum of 12.3 mil. Figure 6 shows Blade 13 after PE1 application was finished.

On February 16, the prescribed sweep blast revealed seventeen small spots (3 x 3 inches) that needed repair. Three of the areas were within the cavitation zone and were repaired with PE1 on March 15. The areas outside the cavitation zone were repaired with three coats of solvent-borne epoxy.

2.5 Blade 7 Application

The team completed the application of the same adhesive used for PE1 to Blade 7 between 10:00 a.m. and 11:00 a.m. on February 8. A thin adhesive layer was brush applied to the roughened ceramic-filled epoxy. The team wore full PPE and isocyanate exposure monitoring equipment. At 1:00 p.m., the team was prepared to start application of PE2 when Skaja noticed that Part A of the coating system was a whiteish wax and was no longer a clear liquid as in prior laboratory applications. The team measured the environmental conditions, with results shown in Table 4, and found that the air temperature was below 65F, the crystallization temperature of Part A. The coatings were placed in an office space and the temperature was set to 85F and left overnight, as instructed on the product data sheet.

Table 4.—Environmental Conditions at 1:00 p.m. on February 8th

Environmental Condition	Measurement
Relative Humidity	40.1%
Ambient Air Temperature	60.7F
Steel Temperature (Ts)	55.4F
Dew Point Temperature (Td)	36.4F
Delta Ts-Td	19.0F

On the morning of February 9, PE2 Part A, after heated storage overnight, was a clear liquid again. Environmental conditions for the application of PE2 were recorded and are shown in Table 5. Each member of the painting team donned full PPE and isocyanate exposure monitoring equipment. The team applied a second coat of adhesive between 7:30 a.m. and 8:30 a.m.

Table 5.—Environmental Conditions Measured Before the Application of PE2 to Blade 7

Environmental Condition	Measurement
Relative Humidity	41.7%
Ambient Air Temperature	60.7F
Steel Temperature (Ts)	57.6F
Dew Point Temperature (Td)	37.3F
Delta Ts-Td	20.3F

Since the ambient temperature was still below 65F, heated welding blankets were used to keep the PE2 components between 75–85F. The heated materials were kept near the draft tube door during application. The heat lowered the viscosity of both components and they mixed easily. The team mixed two kits at a time for about 2 minutes each. When the material started to thicken, the mixed coating materials were handed to the three applicators, as seen in Figure 7. Each batch of two kits covered about 12 sq ft. The team used 36 one-pound kits to cover a total of 210 sq ft. PE2 application was completed by 12:00 p.m. on February 9.

On February 10, the team performed holiday and DFT testing. Three pinholes were found on Blade 7 and repaired using one kit of PE2. The kit was heated in a warm water bath for 15 minutes to reliquefy Part A. The final coating thickness averaged 38.7 mil with a maximum of 79.0 mil and a minimum of 9.1 mil. All areas hardened as expected without any tackiness observed. Figure 8 shows Blade 7 fully coated with PE2.

2.6 Blade 8 Application

A few weeks after the field trial applications of PE1 and PE2, GCD staff finished abrasive blast cleaning the G21 turbine runner and applied three coats of solvent-borne epoxy to the remaining areas, including Blade 8. On March 15, they prepared the epoxy in the cavitation zone areas with a bristle blaster, applied the adhesive, and applied the eight remaining kits of PE2, tapering all terminations to minimize risk of disbondment. The primer profile was not recorded for this application.

On March 22, Skaja inspected Blade 8, documented DFT measurements, and took photos. The DFT of the epoxy adjacent to the cavitation zone was 13 mil average. The final coating thickness of PE2 averaged 40.6 mil with a maximum of 81.0 mil and a minimum of 16.1 mil. All areas hardened as expected without any tackiness observed. Figures 9–11 show Blade 8 coated with epoxy and PE2 coated in the cavitation zone.

3. Results and Discussion

3.1 Blade 13 Inspection at 1,000 hours of Operation

In mid-August, the G21 transformer experienced a failure, and there was a stop in power generation. On October 18, 2023, Grand Coulee staff inspected the PE1 and PE2 cavitation resistant coatings after approximately 1,000 hours of operation. The inspection showed PE1 providing adequate cavitation performance on most of the turbine blade, with approximately 1 square foot of coating damage exposing stainless steel weld overlay in the most severe cavitation zone. This location is near the leading edge on the suction side of the blade, as shown in Figure 12. The few corrosion spots are likely from spot repairs of the application defects and inability to control the coating thickness due to brush and trowel application.

3.2 Blade 7 Inspection at 1,000 hours of Operation

The inspection on October 18, 2023, showed approximately 10 square feet of coating damage in the PE2 repair due to cavitation and delamination between coats, with some areas exposing stainless steel weld overlay in the severe cavitation zone near the leading edge on the suction side of the blade as shown in Figures 13–16.

3.3 Blade 8 Inspection at 1,000 hours of Operation

The inspection on October 18, 2023, accidentally omitted Blade 8 so there is no data at 1,000 hours of operation. The only documentation is showing the leading edge on the upstream side of the blade, with small black specks of coating remaining, shown in Figure 17. Blade 8 will be inspected during the next outage.

3.4 Key Findings

The field trial applications of PE1 on Blade 13 and PE2 on Blade 7 revealed two main challenges, offering good lessons for future use of these materials on a large surface area.

First, for Blade 13, improper mixing ratios of PE1 Parts A and B resulted in areas of incompletely cured product. This was likely due to the relatively short, 13-minute pot life of the system, which presents a challenge for field application. This may have been exacerbated by the exposure assessment requirements—such as wearing full PPE and additional monitoring equipment—which were time consuming and cumbersome. The trial for PE2 did not result in areas of incompletely cured product, which has nearer to a 45-minute pot life. Additionally, PE1 was applied late in the afternoon, requiring the team to work past normal business hours, which increased the stress on individuals to get the materials applied. To improve results in future application, some suggestions are:

- provide a demonstration on how to handle quickly-curing coatings,
- allow team members to perform/witness practice applications and discuss feedback and what can be improved,
- and begin application early enough in the day so that work can be completed within normal business hours.

The second challenge, shown on the Blade 7 application, was that the team had not considered the crystallization temperature of PE2 Part A. It is possible that the use of two coats of adhesive on Blade 7 due to the initial crystallization of PE2 Part A contributed to the disbonded coating. This challenge was overcome by warming up the materials to 85F overnight or by reliquefying for 15 minutes in a warm water bath. An additional solution could be to place the materials in heating blankets prior to use. Future applications can utilize heating blankets or 5-gallon pails of warm water to keep the product components at an appropriate temperature for application.

The application of PE2 on Blade 8 was installed by field personnel with a corrosion resistant primer. The exact details of the application were not documented, and the inspection at 1,000 hours of operation omitted Blade 8. Thus, the outcome is unknown at this time. More information on results, challenges, and lessons learned from the Blade 8 application of PE2 can be determined after the next inspection.

4. Exposure Assessment During Field Trial

PE1 and PE2 are polyurethanes containing 4,4’ methylene diphenyl diisocyanate (MDI) , a known carcinogen and sensitizer. Concern over the health hazards of MDI requires the highest level of worker protection. Full PPE for the painting team included supplied air respirators, Tychem suits, and chemical resistant gloves.

The OSHA and NIOSH permissible exposure limit (PEL) of MDI is 5 parts per billion (ppb) time weighted average (TWA) for an 8-hour shift. The ceiling PEL is 20 ppb for a 10-minute exposure. MDI monitoring for isocyanate exposure was done following NIOSH Method 5521 to monitor the breathing zone for the two applicators and the two people mixing [4]. The team used Gilair Plus air monitoring pumps equipped with Iso-Check® cassettes (for the TWA) and Asset® tubes (for the ceiling PEL). The tubes were kept on for the duration of the application. Once the application was complete, the tubes were removed and processed for shipping to a lab for analysis. For PE1 application, cassettes showed non-detectable for the adhesive and coating systems; the tubes showed a maximum exposure of 0.17 ppb during the adhesive application, and non-detectable for the coating application. No Iso-Check or Asset tube data was collected for PE2 due to the postponed application.

In addition, when entering the turbine runner, each team member wore a Morphix Company's SAFEAIR colorimetric badges for toluene diisocyanate/MDI near the breathing zone for a visual assessment to monitor exposure of everyone. The colorimetric cards were used to indicate immediately if any individual was exposed and at what concentration. None of the colorimetric cards showed exposure. One card was dabbed with the adhesive product to confirm it was working, and it turned bright red.

For future applications of these systems in similar conditions, respirators or powered air purifying respirators (PAPRs) with air purifying cartridges could be worn in lieu of supplied air lines when brush or troweling is used. Note that chemical-resistant clothing and gloves should always be worn to limit dermal exposure.

Work and safety plans and the Job Hazard Analysis (JHA) for this field trial are available for internal Reclamation employees. Contact TSC project lead, Allen Skaja (askaja@usbr.gov), for more information.

5. Conclusions

- Two polyurethane elastomer coating materials were successfully applied to Blades 7, 8, and 13 of Unit G21 turbine runner. Lessons learned and best practices on application are documented in this report for future reference.
- Initial field results show that after 1,000 hours of operation, the PE1 and PE2 coatings show small areas of damage, found mostly on the areas of the turbine runner blade that experience the most severe cavitation environment.
- Blade 7 showed the most damage, approximately 10 square feet, possibly due to having two adhesive coats because of the PE2 Part A crystallization delaying the application one day to re-warm. Blade 13 showed approximately 1 square foot of damage. The damage location was consistent for both and in the severe cavitation zone near the blade leading edge.
- Overall, the field application could have improvements for ease of application of the polyurethane elastomers, the adhesive, and the epoxy primer.
- Air monitoring pumps equipped to assess TWA and PEL showed non-detectable respirable or below the action level for MDI according to OSHA and NIOSH limits during the application of the adhesive and PE1.

- Visual MDI-indicators worn by each member inside the turbine runner showed no exposure to respirable MDI during the applications of the adhesive, PE1, and PE2.

Recommendations for Grand Coulee Nathaniel "Nat" Washington Power Plant:

- Grand Coulee should record the total run time of Unit G21 and operating conditions. GCD should allow inspections during outages to determine the coating system performance. Detailed photos showing location and scale should be taken and provided to the TSC project lead, Allen Skaja (askaja@usbr.gov).
- For future applications of these systems in similar conditions, respirators or powered air purifying respirators (PAPRs) with air purifying cartridges could be worn in lieu of supplied air lines when brush or troweling is used. Note that chemical-resistant clothing and gloves should always be worn to limit dermal exposure.

6. References

[1] A. H. C. Skaja, "Investigation of Polymeric Elastomers for Cavitation and Erosion Resistance," in *AMPP Conference*, Denver, CO, 2023.

[2] NACE/ SSPC, "NACE 1/ SSPC-SP5 White Metal Blast Cleaning," NACE/ SSPC, Houston, TX, 2006.

[3] NACE SSPC, "NACE 4/ SSPC-SP 7 Brush-off Blast Cleaning," NACE SSPC, Houston, TX, 2006.

[4] National Institute of Occupational Safety and Health, "NIOSH Method 5521 Isocyanates, Monomeric," NIOSH, Washington, DC, 1994.

7. Figures

Figure 1.—Typical condition of surface preparation at 308 stainless steel weld overlay/mild steel transition.


Figure 2.—The surface of Blade 13 primed with ceramic-filled epoxy, shown after sweep blasting.

Figure 3.—Measurement of environmental conditions on Blade 13 prior to the application of adhesive.

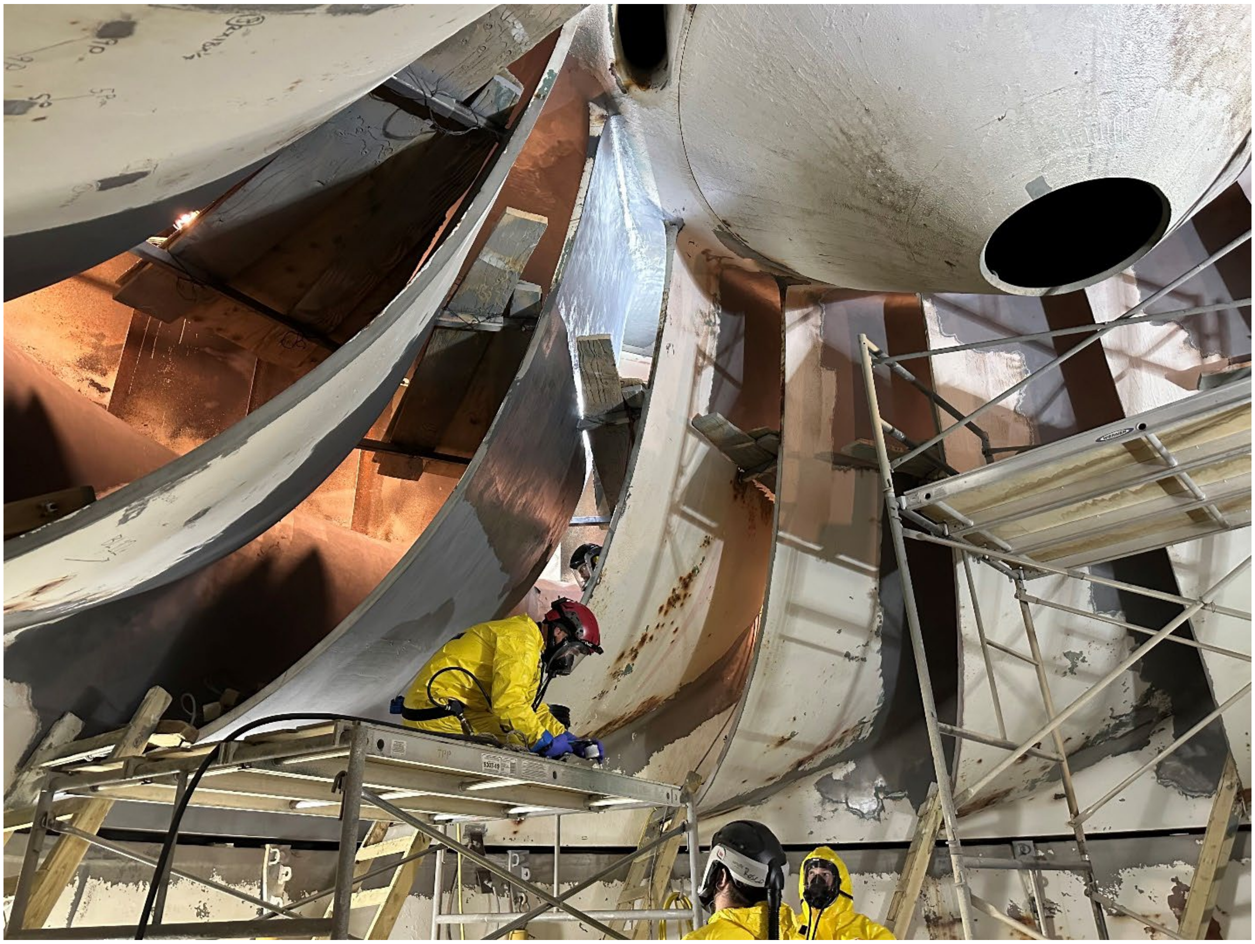
Figure 4.—The team applies adhesive to Blade 13.

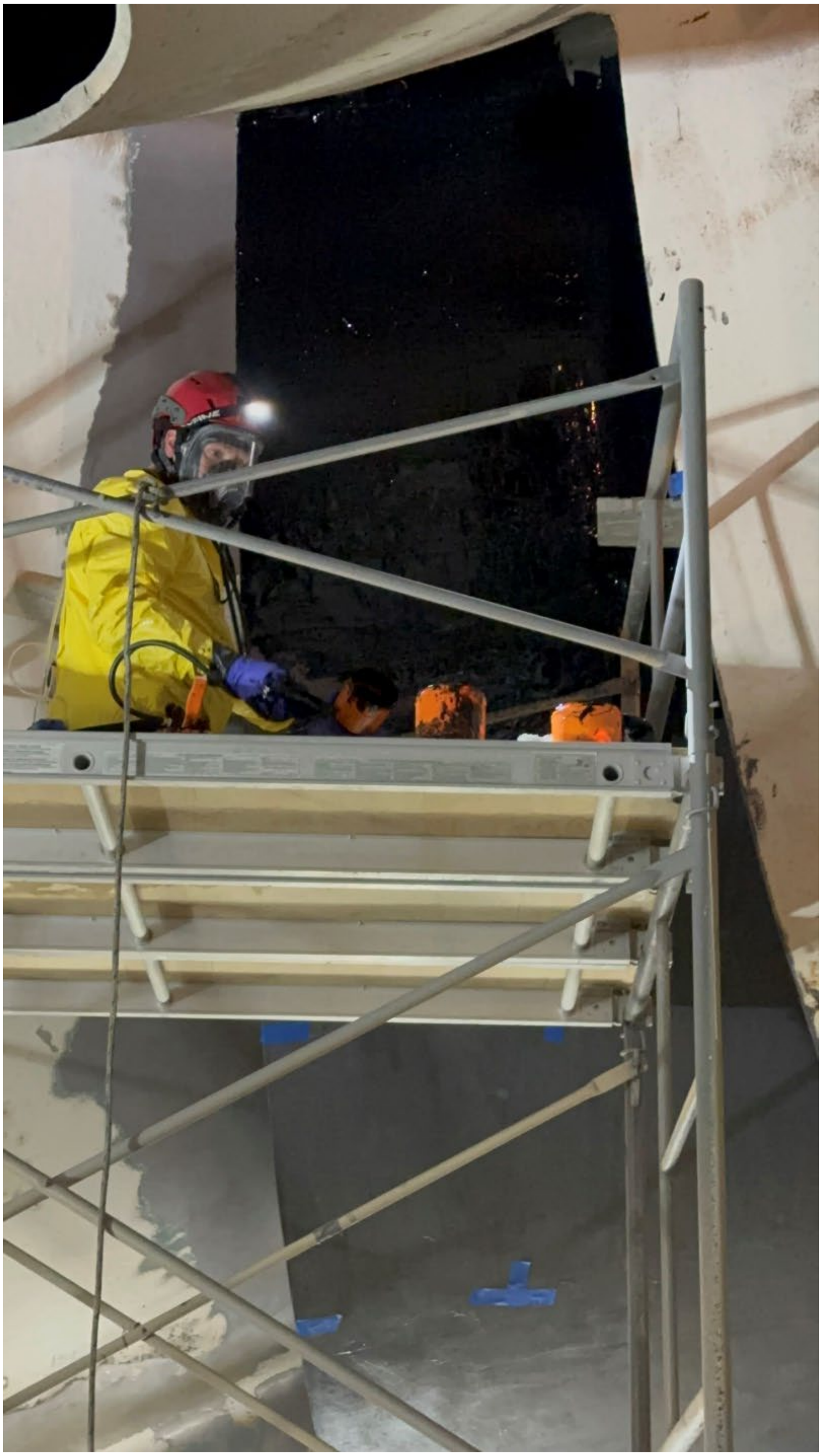

Figure 5.—Application of PE1 to Blade 13.

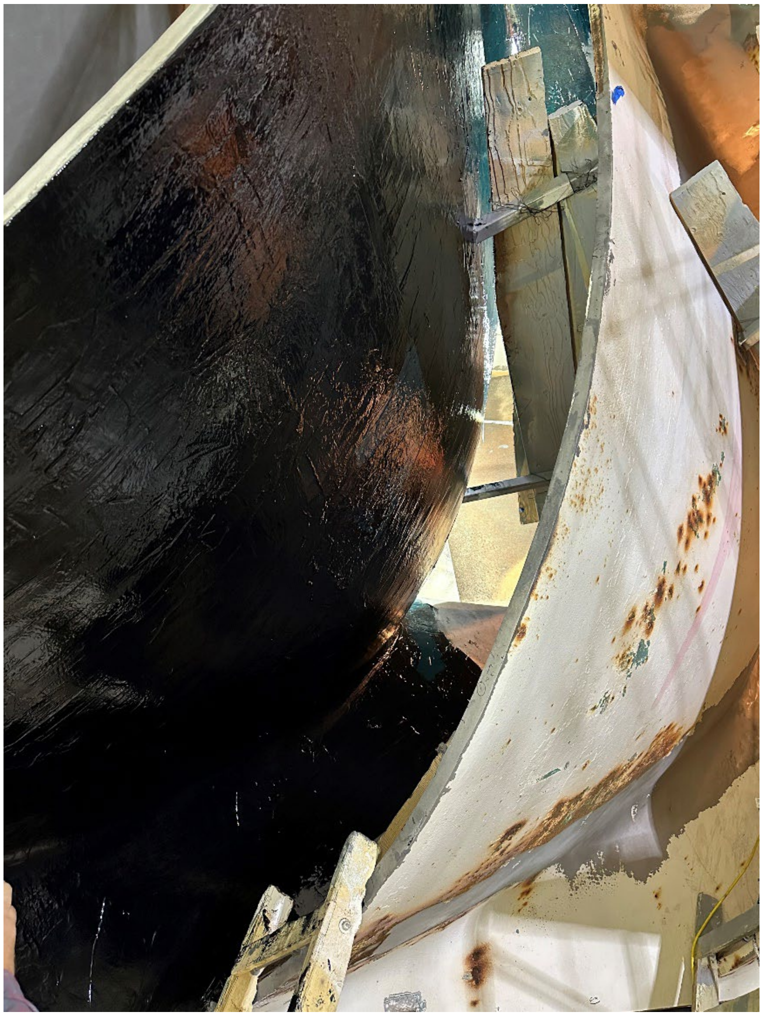
Figure 6.—Blade 13 shown coated with PE1.


Figure 7.—Application of PE2 to Blade 7.

Figure 8.—Blade 7 shown coated with PE2.

Figure 9.—The cavitation zone of Blade 8 shown coated with solvent-borne epoxy and PE2.


Figure 10.—The cavitation zone of Blade 8 shown coated with solvent-borne epoxy and PE2.

Figure 11.—The cavitation zone of Blade 8 shown coated with solvent-borne epoxy and PE2 before exposure.

Figure 12.—Cavitation damage on leading edge suction side of PE1, approximately 1 square foot of damage. The gray color is from application defects that were repaired with an epoxy.

Figure 13.—Blade 7 after 1,000 hours of operation. The PE2 failed by cavitation and delamination on leading edge with approximately 10 square feet of damage. The rust spot near the center of the blade is from the welded brace that was removed for the platform and repaired using an unknown procedure.

Figure 14.—Close-up of Blade 7 after 1,000 hours of operation. The PE2 failed by cavitation and delamination on leading edge.

Figure 15.—Close-up of Blade 7 after 1,000 hours of operation. The PE2 failed by cavitation and delamination.


Figure 16.—Close-up of Blade 7 after 1,000 hours of operation. The PE2 failed by cavitation and delamination.

Figure 17.—Leading edge of Blade 8 showing the applied PE2 almost completely gone, with only a few specks of the black coating still remaining after 1000 hours. No photos are available of the downstream side of the blade shown in Figure 11.

Appendix C— Flatiron Powerplant Field Trial

BUREAU OF RECLAMATION

Flatiron Powerplant Unit 2 Butterfly Valve Cavitation Resistant Coating Field Trial

Interim Report No. ST-2023-20024-03
Technical Memorandum No. 8540-2023-34

Big Thompson Project, Colorado
Missouri Basin Region

C-2

U.S. Department of the Interior

December 14, 2023

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14. ABSTRACT Flatiron Powerplant butterfly valves experience cavitation since the seats were replaced with stainless steel in 2010. Different linings have been used to reduce cavitation damage on the downstream side of the butterfly valves, with minimal success. Laboratory testing identified two commercial polyurethane elastomers that may provide better cavitation resistance than prior linings used in draft tubes for cavitation resistance. The two lining materials were selected for field trials on a Flatiron Powerplant Unit 2 butterfly valve as a cavitation repair material for filling the entire cavitation pit, i.e., without stainless steel weld repair. The butterfly valve has a moderate cavitation environment with an approximate pressure drop of 500 pounds per square inch.						
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Flatiron Powerplant Unit 2 Butterfly Valve Cavitation Resistant Coating Field Trial

Interim Report No. ST-2023-20024-03
Technical Memorandum No. 8540-2023-34

Big Thompson Project, Colorado
Missouri Basin Region

prepared by

Technical Service Center
Materials and Corrosion Laboratory Group
Allen Skaja, Ph.D. Protective Coatings Specialist

Cover photograph: Area on interior of penstock showing the test coating fully applied.

Peer Review

Bureau of Reclamation
Technical Service Center
Materials and Corrosion Laboratory Group

Interim Report No. ST-2023-20024-03
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Flatiron Powerplant Butterfly Valve Cavitation Resistant Coatings Field Trial

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Contents

Executive Summary

Hydroelectric powerplants must conduct cavitation repairs every few years to slow cavitation damage on components subjected to high flow conditions that contain a pressure drop, such as the downstream side of butterfly valves and turbine runners. Through recent laboratory testing, the Technical Service Center (TSC) has identified two polyurethane elastomers (materials with rubber-like properties) which demonstrate superior cavitation resistance compared to other lining materials tested. The laboratory test data indicate these two lining materials, PE1 and PE2, may provide protection in moderate or severe cavitating environments that is comparable to stainless steel weld overlays, the traditional approach to providing cavitation resistance in high flow areas.

In February 2023, TSC applied field trials of PE1 and PE2 to Nathaniel Washington Powerplant Unit G21 turbine runner [1]. TSC needed a separate field trial to evaluate these materials for use as fillers to repair cavitation pits. The Unit 2 butterfly valve at Flatiron Powerplant was chosen for the trial. The downstream side of the valve body exhibited 3/8-inch-deep cavitation pits, resulting from the 500-pound-per-square-inch pressure drop caused by water seeping around the seats when the valves are in the closed position. Trial repairs were conducted on March 28, 2023.

The cavitation areas of the butterfly valve body were power tool cleaned to bare metal, per SSPC-SP11, using angle grinders, needle guns, and a bristle blaster [2]. An adhesive was applied directly to bare metal and allowed to cure. PE1 and PE2 were applied in accordance with the product datasheets. Each elastomer was applied to approximately 3 linear feet within the cavitation damage zone. PE1 filled the entire 3/8-inch-deep pit without sagging. PE2 sagged and dripped out of the deep pits, requiring a second coat. The field trial commenced on April 11, 2023, when the penstock was watered up with the valve in the closed position. Flatiron power plant is not scheduled for an outage until March 2025, and the cavitation repair trial will be evaluated during this outage.

1. Background

Hydroelectric powerplants must conduct cavitation repairs every few years to slow cavitation damage on components subjected to high flow conditions, such as the downstream side of butterfly valves or turbine runners. The Research and Development Office's Science and Technology Program funded project number 20024, Field Repairable Materials and Techniques for Cavitation Damage, a laboratory research effort which evaluated 24 commercial lining materials for cavitation resistance [3]. The tests subjected the candidate materials to high-velocity impinging water conditions, and compared the results to type 316 stainless steel, ASTM A36 mild steel, and type 308/309 stainless steel welds overlaid on mild steel, which is the traditional approach for providing cavitation resistance to components in the field. Two polyurethane elastomers (materials with rubber-like properties) showed excellent cavitation resistance in the laboratory testing, performing comparably to 308/309 stainless steel weld overlays. The other 22 lining materials exhibited damage within eight hours of the lab testing conditions. Some of those materials have been used in draft tubes with mild cavitating environments and have shown satisfactory performance. These cavitation resistant coatings failed around 8 hours under laboratory testing. The top two performing polyurethane elastomers, PE1 and PE2, failed around 150 hours in laboratory testing and might perform well in more aggressive or moderate cavitation environments. Table 1 provides typical observations for the varying severity of cavitation intensity. Field trials are necessary to determine if these materials can provide improved cavitation prevention to traditional mitigation methods. One goal of this study is to increase the service life or maintenance cycles of cavitation repairs, which could reduce facility maintenance costs.

Table 1.—Cavitation severity levels defined for this research based on the damage level observed in traditional polymer coatings, mild steel, Type 308/309, and 316-series stainless steels after 200 hours of laboratory testing or an estimated 10,000-hour exposure in the field.

Cavitation Level	Traditional Polymer Coatings	Mild Steel	Type 308/309 Stainless Steel	Type 316 Stainless Steel
Mild	Volume loss and some complete removal	Light frosting/ minor metal loss	No damage	No Damage
Moderate	Complete removal	Moderate metal loss	Light frosting	No Damage
Severe	Complete Removal	Severe metal loss	Moderate metal loss	Light frosting
Extreme	Complete Removal	Severe metal loss	Severe metal loss	Moderate metal loss

2. Field Trial Details

PE1 and PE2 were applied to the Nathaniel Washington Powerplant Unit G21 turbine runner in February 2023 as the first field trial of cavitation resistant coatings with total applications of 20–50-mil dry film thickness [1]. A separate field trial was needed to evaluate the lining materials as fillers to repair cavitation pits with applications exceeding 3/8-inches (375-mil) dry film thickness. Researchers selected the Unit 2 butterfly valve at Flatiron Powerplant for the second trial location. Trial repairs were applied on March 28, 2023 and the trial commenced when operations resumed on April 11, 2023.

2.1 Surface Preparation

The downstream side of the valve body, shown in Figure 1–Figure 2, exhibited 3/8-inch-deep cavitation pits, resulting from the 500-pound-per-square-inch (psi) pressure drop caused by water seeping around the seats when the valves are in the closed position. On the morning of March 28, 2023, the area was cleaned with needle guns and a bristle blaster to prepare the cavitated areas of the butterfly valve body to bare metal conditions per SSPC-SP11, as shown in Figure 3–Figure 5 [2].

2.2 Adhesive Application

Following surface preparation, Flatiron Powerplant staff brush-applied a thin coat of clear adhesive to all cavitation areas. Surface temperature was measured and recorded at 49 degrees Fahrenheit following the adhesive application, prior to the elastomer applications. No epoxy primer was used in this application and the adhesive was applied direct to metal. The adhesive was worked into the cavitation pits to evenly coat the cavitation pitted surfaces.

2.3 Application of Polyurethane Elastomer 1

PE1 was mixed for three minutes and applied to its test area between the 8 o'clock and 11 o'clock positions, and across the trunnion at the 9 o'clock position. The lining was worked into the surface profile and cavitation pits with a thin initial layer using brushes. The lining was applied in layers until all pits were filled. A trowel was used to periodically smooth any sags until the viscosity held the elastomer in place and no further sags formed. Figures 6–7 show the PE1 test area after the final application.

2.4 Application of Polyurethane Elastomer 2

PE2 was mixed for three minutes and applied to its test area between the 11 o'clock and 1 o'clock positions and between the 7 o'clock and 8 o'clock positions. The lining was worked into the surface profile and cavitation pits with a thin initial layer using brushes. The lining was applied in layers until all pits were filled. A trowel was used to periodically smooth any sags, but sags continued to form, as the viscosity of this coating was lower than PE1 and it never increased to a point where it would stay entirely in place. Figures 8–10 show the test area after application of the first coat. A second coat was applied on March 29, 2023. Once the second coat had cured, remaining drips and sags were ground smooth with an angle grinder. Figure 11 shows the competed field trial cavitation repair area.

3. Discussion

The field trial at Flatiron repaired cavitation pits up to 3/8-inch deep with two unique polyurethane elastomers, PE1 and PE2, instead of using the traditional 308/309 stainless steel weld repair technique.

The field trial will determine the effectiveness of polyurethane elastomer linings in a moderate cavitating environment. If successful, these linings could be used as repair material alternatives to 308/309 stainless steel weld overlays in moderate cavitation environments with comparable or improved performance. These materials could provide powerplants greater flexibility in maintenance and operation decisions.

4. Conclusions

- The Flatiron Powerplant field trial is a complementary trial to the Nathaniel Washington powerplant field trial [1]. The Flatiron Powerplant test will determine if two polyurethane elastomer lining materials, PE1 and PE2, are suitable for bulk cavitation repairs to fill pits up to 3/8-inch thick. The same lining materials are being tested at Nathaniel Washington as 20–50 mil (dry film thickness) linings, applied after cavitation pits had been repaired with 308/309 stainless steel weld overlays.
- Two polyurethane elastomer lining materials were successfully applied to the downstream side of the butterfly seat on Unit 2. Instead of using a stainless steel weld overlay to make the repairs, the lining materials were used to fill cavitation pits.
- Polyurethane elastomer field trials will determine the effectiveness of these lining materials in moderate cavitating environments.

Recommendations for Flatiron Power Plant:

- Record the total run time of Unit 2 and the time the butterfly valve was in the closed position, which causes cavitation.
- Conduct inspections when there are outages and document the appearance of the test areas. Provide detailed photos to the TSC project lead, Allen Skaja (askaja@usbr.gov).

5. References

[1] Skaja, A., Interim Report ST 2023-20024-02 "Grand Coulee Dam G21 Turbine Runner Cavitation Resistant Coating Field Trial" Bureau of Reclamation, Denver CO, 2023.

[2] SSPC-SP11, "Powertool Cleaning to Bare Metal," SSPC, Pittsburgh, 2020.

[3] Skaja, A., Henderson, C., "Investigation of Polymeric Elastomers for Cavitation and Erosion Resistance," 2023 AMPP Conference, Denver CO, March 20, 2023.

6. Figures

Figure 1.—Condition of the cavitation damage downstream of the butterfly seat (left side of stainless steel seal) prior to surface preparation.

Figure 2.—Condition of the cavitation damage downstream of the butterfly seat prior to surface preparation.

Figure 3.—Power tool cleaning to metal of the cavitation damage downstream of the butterfly seat. The blue tape is protecting the stainless steel seat. The 3/8-inch-deep cavitation damage is to the left of the tape.

Figure 4.—Powertool cleaning to metal of the cavitation damage downstream of the butterfly seat. The blue tape is protecting the stainless steel seat. The 3/8-inch-deep cavitation damage is to the left of the tape.

Figure 5.—Cavitation damage downstream of the butterfly seat shown after power tool cleaning exposed pits up to 3/8 inches deep.

Figure 6.—PE1 is shown applied between the 9 o′clock and 11 o′clock positions.

Figure 7.—PE1 is shown applied between the 8 o’clock and 9 o’clock positions.

Figure 8.—PE2 is shown applied between the 11 o’clock and 1 o’clock positions.

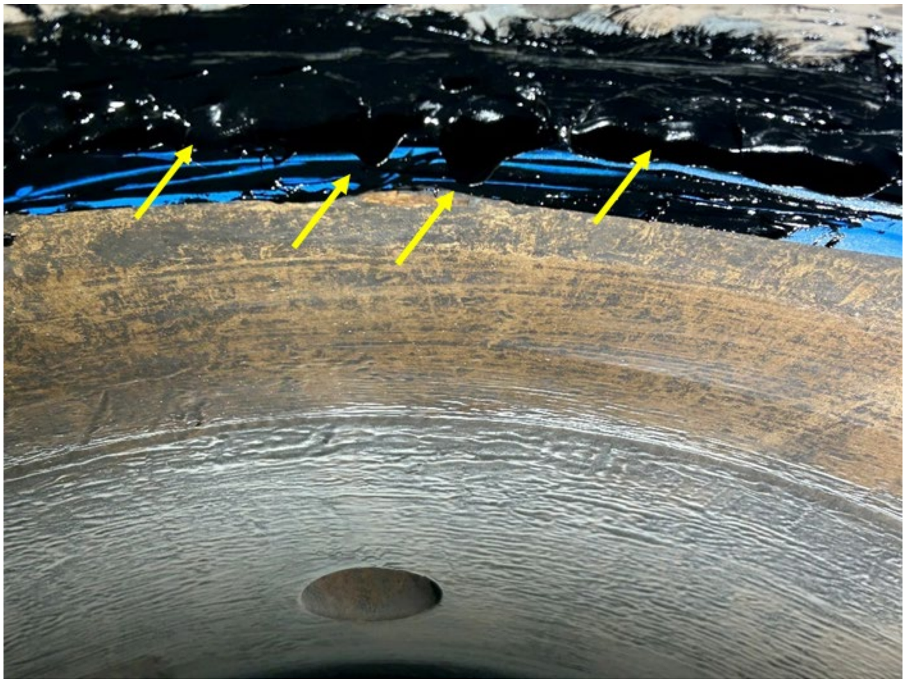

Figure 9.—PE2 is shown applied between the 11 o’clock and 1 o’clock positions. The lower viscosity resulted in sags and drips, noted with arrows.

Figure 10.—PE2 is shown applied between the 7 o’clock and 8 o’clock positions.


Figure 11.—Test area is shown prior to recommissioning Unit 2 penstocks. Drips and sags had been smoothed, but a few areas still needed to be sanded down to allow for proper operation of the butterfly valve.