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Test Method Development for Adhesion Strength of Protective Coatings under Real-Life Hydraulic Conditions

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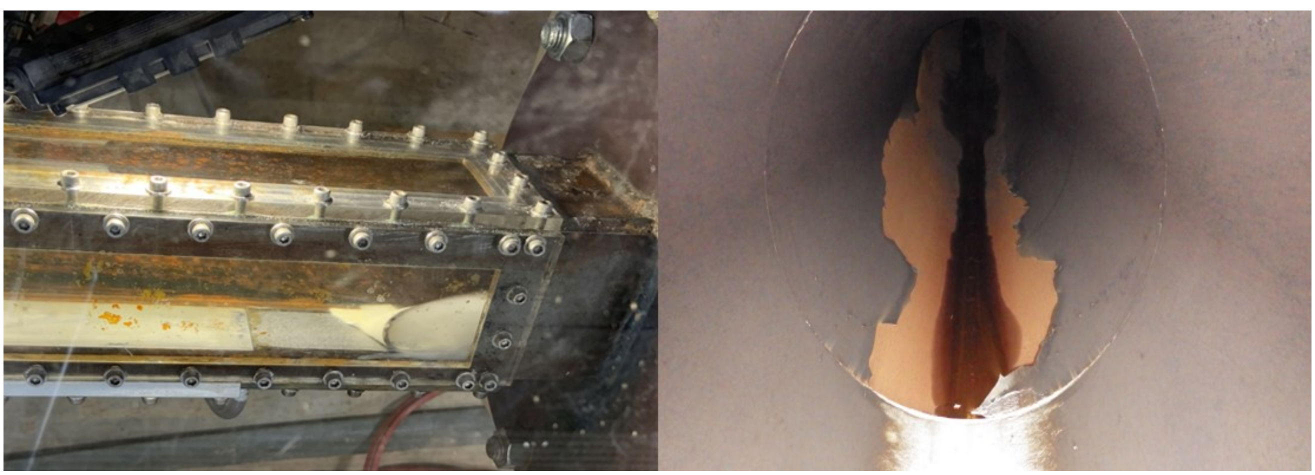

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14. ABSTRACT

Recent field experience with modern protective coating systems has shown that traditional test methods for coating adhesion do not provide reliable results. In the current study, efforts were made to develop a test method for coating adhesion strength that simulates hydraulic conditions present in the field to improve correlation between laboratory results and field experience. The method combines laboratory measurements and boundary layer theory to directly compare hydraulic parameters from the laboratory and field. To date the test method, which exposes coating test samples to hydraulic uplift forces that cause coating delamination, used polyurethane coating test samples to directly compare laboratory and field results as well as other trial coating systems. Laboratory results showed greater uplift forces required to delaminate coatings compared to those predicted from failures in the field. More detailed analyses of field case studies as well as refinements to the laboratory test method (i.e. increased exposure time and approach velocity) will help to improve the test method to better correlate laboratory and field results.

15. SUBJECT TERMS
Adhesion, coatings, delamination, failure, penstock, stagnation pressure, uplift

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Test Method Development for Adhesion Strength of Protective Coatings under Real-Life Hydraulic Conditions

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Acronyms and Abbreviations

CFD	Computational Fluid Dynamics
ft/s	feet per second
ft^3/s	cubic feet per second
NRL	Naval Research Laboratory
PIV	Particle Image Velocimetry
Psi	pounds per square inch
Reclamation	Bureau of Reclamation
VFD	Variable Frequency Drive

Contents

Executive Summary

Protective coating systems are used on a wide range of hydraulic equipment that are submerged in water such as power penstocks, outlet pipes, gates, valves, and trash racks. On these equipment coatings are exposed to high discharge velocity which may induce uplift forces, turbulence, pressure fluctuations, and cavitation. Much of this equipment, especially penstocks and outlet pipes, has been coated with coal tar enamel in the past which has performed very well but is reaching the end of its service life in many facilities. Since coal tar enamel linings can no longer be replaced due to environmental and safety reasons, finding dependable coatings with good adhesion and durability characteristics for long service life is an ongoing challenge for Reclamation. A reliable test method that can better predict adhesion performance in actual field conditions is important for future coatings applications.

The main objective of this study was to develop a laboratory test method to evaluate the adhesion strength of coatings systems with real-life conditions of the environment in which they are applied. While standard test methods for coating adhesion exist, most are mechanical in nature and their laboratory results have not correlated well with field experience. A test method is needed that replicates the submerged conditions and hydraulic forces to which coatings may be exposed in a field environment to improve the reliability of test data.

In this study small representative coating samples were subjected to high discharge velocities to create uplift pressure at full scale. This test approach utilized measurements of the uplift force and approach velocity, coupled with visual observations, that help describe the behavior and mode of failure of the coating samples. The following conclusions and recommendations should be considered for future adhesion testing with the current test facility and procedure.

- The test facility and procedure developed in Reclamation's Hydraulics Laboratory successfully simulated field-scale approach velocities and uplift forces to fail coating systems by adhesion. The test method could be improved by increasing the upper limit of approach velocities within the test chamber and increasing the exposure time of each flow condition.
- Some coatings could not be tested due to difficulty in creating the upstream "flap" (coating not adhered to base material) needed to initiate coating failure. The upstream "flap" should be created as part of the coating application process rather than cutting or machining it on the metal test sample after it has already been coated. Corrosion undercutting is what causes the "flap" in field conditions from coating damage. This is especially true for thin coatings (≈15-20 mils) and coatings that are sensitive to heat such as coal tar.
- For Polyurethane coatings, test results from the laboratory showed a greater uplift pressure required for failure compared to coating failures in the field. This may be due to several factors including unknown localized hydraulic conditions acting on the field coating, the amount of underlying corrosion, and the extent that the upstream edge of the coating defect was lifted into the high discharge velocity. While all these factors cannot be accounted for in a laboratory test,

further investigation into the hydraulic conditions of failures in the field will likely improve the correlation of laboratory testing and field experience.

Introduction

Protective coating systems are used on a wide range of hydraulic equipment that are submerged in water such as power penstocks, outlet pipes, gates, valves, and trash racks. On these equipment coatings are exposed to high discharge velocity which may induce uplift forces, turbulence, pressure fluctuations, and cavitation. Much of this equipment, especially penstocks and outlet pipes, has been coated with coal tar enamel in the past which has performed very well but is reaching the end of its service life in many facilities. Since coal tar enamel linings can no longer be replaced due to environmental and safety reasons finding dependable coatings with good adhesion and durability characteristics for long service life is an ongoing challenge for Reclamation. A reliable test method that can better predict adhesion performance in actual field conditions is important for future coatings applications.

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Project Background

The need for more robust test methods for coatings stemmed from a research priority identified in the Research Roadmap for Hydropower Units [1] and development began with a scoping study soon after [2]. The scoping study produced a summary of literature findings related to existing coatings test methods and field experience and included discussions from coatings experts from the Naval Research Laboratory (NRL). They have also experienced significant differences in laboratory test data and field results for new coatings applications on hulls and propellers for ships and sub-marines. Findings from the literature and discussions with NRL lead to the decision that new test method development should focus on coating adhesion. The scoping level report states:

"While attempts will be made to account for the dominant processes that lead to coating failure by delamination (failure of adhesion strength), it will be impossible to truly represent every condition seen in a field application. Other variables such as surface condition of the penstock during application, size and geometry of damage or flaws in the coating that initiate the delamination process, temperature variations, sediment laden flow, debris, and exposure time all contribute to the service life of a coating system. While these conditions all have an influence, the findings of this scoping-level study point to accurate test methods of adhesion strength as the greatest need for extending service life of coatings at this time."

Recent experience with new coating systems in the field also showed the need for an improved adhesion test method. In 2015 failure of the penstock lining occurred at Flatiron hydropower plant where approximately 40 ft of the coating delaminated (Figure 1) and caused major issues for the downstream hydropower unit [3]. The coating system had only been in service for four years. Similar incidents of delaminated coatings occurred for the same coating system at Enders Dam in 2016 (Figure 2) and Platoro Dam in 2019 (Figure 3). At Enders coating delamination began at a few locations, namely the connection between the outlet pipe and the downstream control valve. For Platoro [4], delamination initiated at a pipe joint in the left bifurcation of the outlet works about five feet upstream of the control gate. Fortunately, in both cases initial delamination was caught before major damage occurred. Upgrades to lining systems in penstocks and outlet pipes are expensive (2-5 million dollars) due to large surface areas to be prepared and lined, as well as extra safety precautions for working in confined space with steep slopes.

While the extent of damage in these cases varied significantly, the common factor was that hydraulic uplift forces appeared to be the dominant factor leading to delamination of the coatings. In each case the delamination initiated at a discontinuity of the inner pipe wall, generally at a pipe joint. Water flow entered beneath the lining and pressures between the coating and pipe wall caused the coating to peel away from the pipe wall. This is the same physical process that can lift concrete slabs at joints in spillways and cause catastrophic damage like the Oroville Dam incident in 2017 [5]. The root cause of initial flow penetration beneath the coating is not known but could be due to a variety of factors (i.e. underlying corrosion, defect due to offset geometry, movement or vibration of offset, etc). While all these factors cannot be accounted for in the laboratory the dominant physical processes that cause the coatings to delaminate from the pipe wall can be simulated at field-scale in the laboratory.

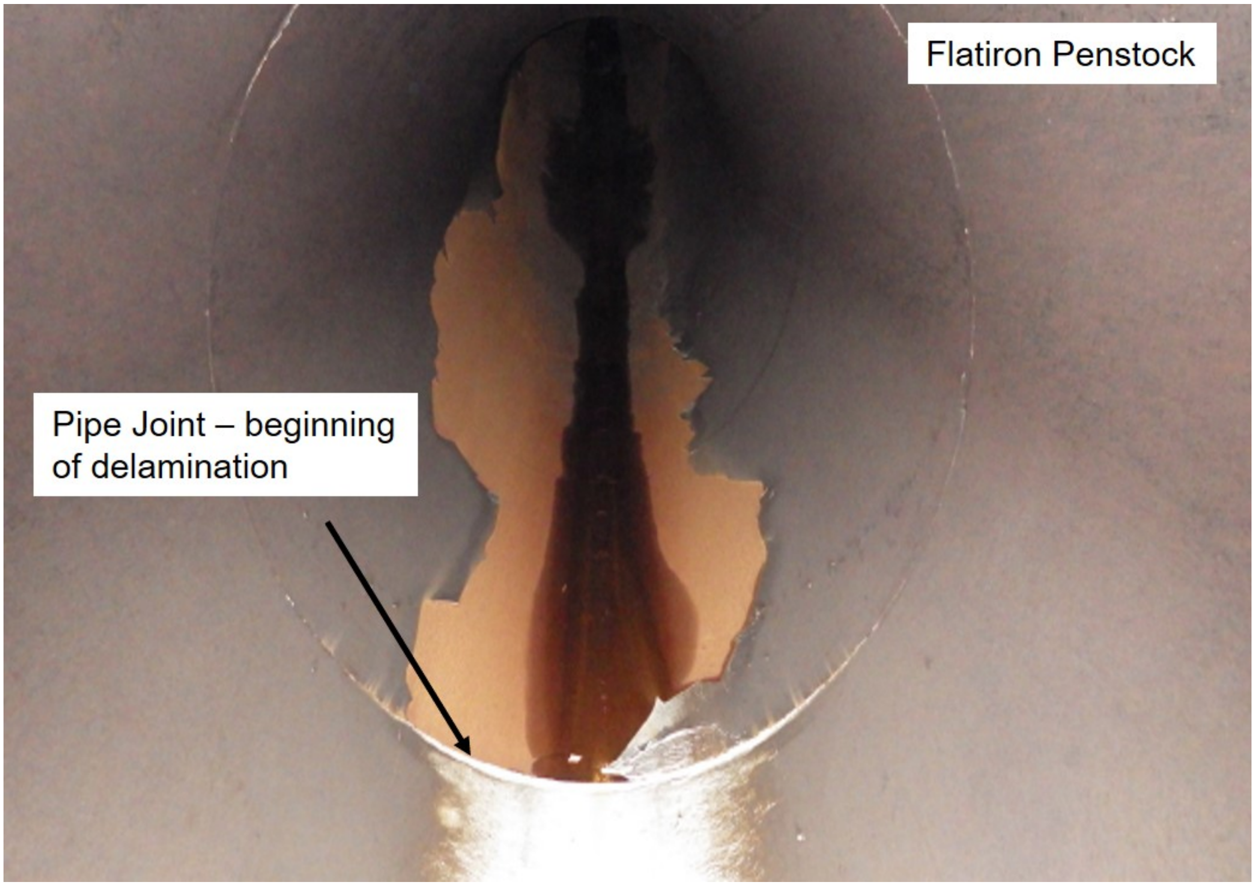

Figure 1 Photo of the 2015 polyurethane lining failure at Flatiron penstock, looking downstream.

Figure 2 Polyurethane lining delamination at connection of outlet works pipe and control valve at Enders Dam in 2016. Flow is right to left.

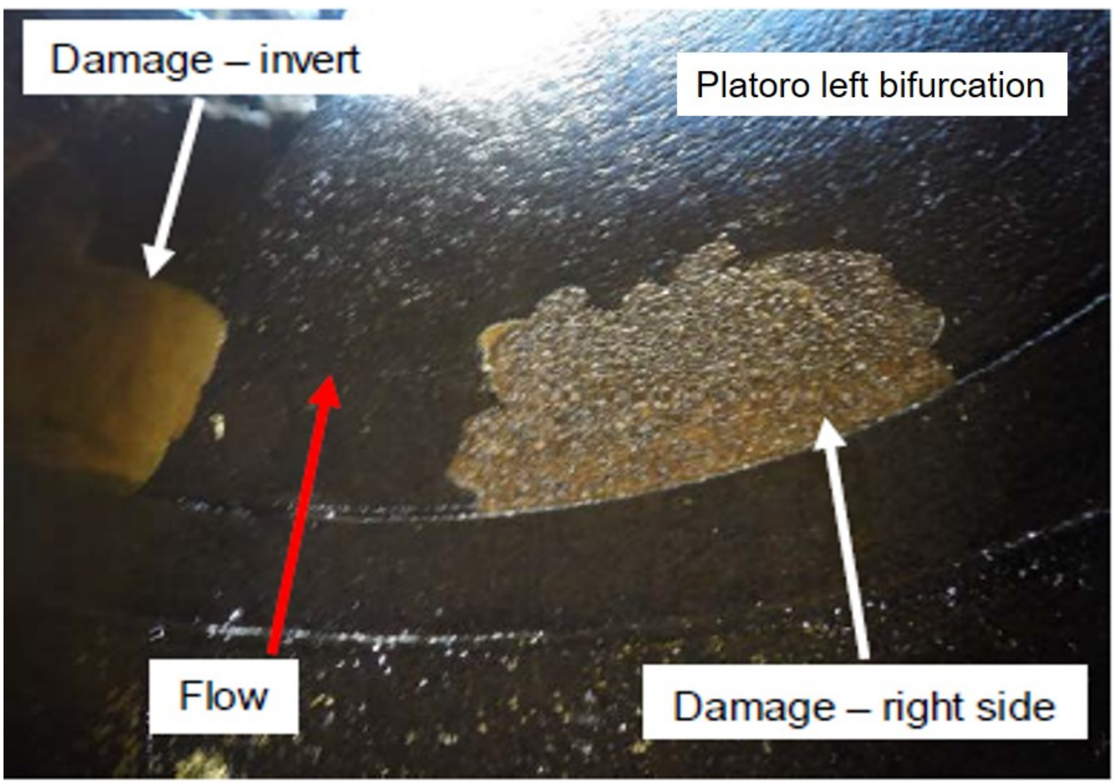

Figure 3 Polyurethane lining delamination at a pipe joint in the left bifurcation of the outlet works at Platoro Dam, 2019. Looking downstream.

Approach

Simulating Real-Life Hydraulic Conditions

As findings from the literature and field experience pointed to hydraulic uplift as the dominant force causing delamination of coatings, a test approach was developed to simulate these forces in the laboratory. Uplift forces are generated by flow velocities acting on the upstream side of a coating defect and penetrating the underside of the coating as shown in Figure 4. This causes a stagnation pressure to lift the coating away from the boundary to which it is adhered. Stagnation pressure is a function of the streamwise velocity near the boundary and is defined in equation 1. While localized turbulence and even cavitation may act on the coating defect the uplift force produced by the stagnation pressure is believed to be the main cause of delamination.

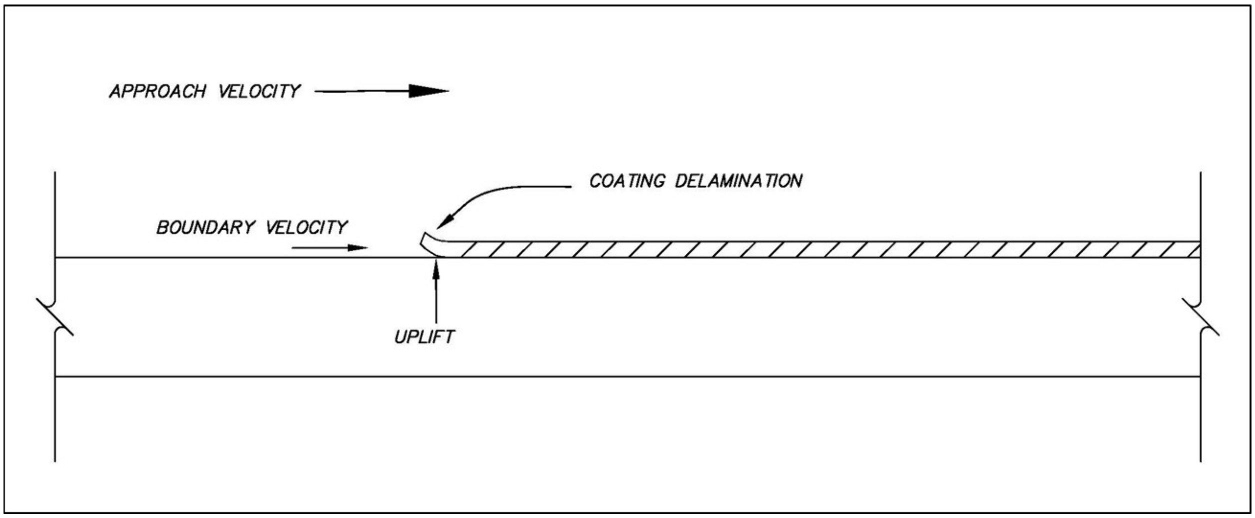

Figure 4 Schematic of dominant hydraulic forces causing the coating delamination from the pipe wall.

$$P_s = \frac{1}{2}\rho {V_y}^2 \quad (1)$$

Where:
P_s = Stagnation pressure (lb./ft^2)
ρ = density of water (slug/ft^3)
V_y = streamwise boundary layer velocity at 50% of coating thickness (ft/s)

Since stagnation pressure depends on the velocity at the coating it is important to accurately predict the localized velocity near the boundary. Due to the roughness and friction of the pipe wall the velocity near the wall boundary is reduced compared to velocity near the center of the pipe as presented by the schematic in Figure 5. The schematic also shows a steep velocity gradient near the boundary.

Considering protective coating systems vary between 15 and 80 mils in thickness, depending on the brand, the boundary layer velocity and resulting stagnation pressure could vary widely. This depends on whether the coating is within the "viscous sublayer" where velocities are quite small or protrudes into the outer layer and is exposed to higher velocities. Prediction of stagnation pressures acting on the coating depends on coating thickness, discharge, and geometry of the conduit.

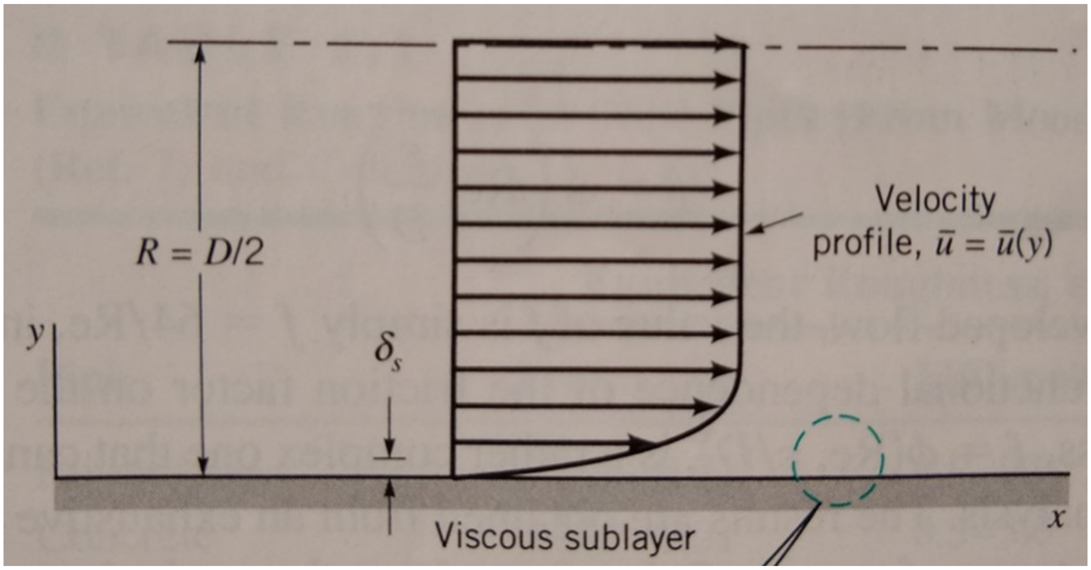

Figure 5 Schematic vertical velocity profile to illustrate significant reduction in flow velocity near the boundary, from Munson et al [6]

For fully developed flow the velocity at any given distance from the boundary can be predicted using empirical equations [7]. For locations or geometries where the velocity profile is not fully developed (still changing with distance within the conduit) physical measurements or numerical hydraulic simulations are needed to accurately predict velocities close to the boundary. The test chamber in the current study simulates these hydraulic conditions at field scale. Approach velocities (average velocity over the cross-sectional area) and uplift pressures were measured in the laboratory test facility. Velocity profiles near the boundary were simulated with a Flow3D Computational Fluid Dynamics (CFD) model but not reported here as they need to be further compared to physical measurements.

The benefits of this test approach and facility include field-scale velocities and uplift pressures that are directly measured and compared to coating performance and the use of a "wet" test method where the coating samples are continuously submerged, eliminating uncertainties related to mechanical test methods performed in the dry. The intent is that results from the current test method can be directly compared to field cases and their specific hydraulic conditions.

Laboratory Test Facility

Layout

A test facility was constructed in the Bureau of Reclamation's Hydraulics Laboratory located in Denver, Colorado for coating adhesion testing. The test facility was capable of controlling uplift pressure to the samples by varying the velocity approaching the coating offset within the range of 15 ft/sec to 55 ft/sec. The facility and system included a 100 hp pump controlled by a variable frequency drive (VFD), a flow straightener in the upstream pipe to create uniform flow field approaching the test section, a reducing transition from circular pipe to the rectangular test section (3-inch by 3.5-inch) where coating samples were mounted, and an expanding transition from the test section to 12-inch circular pipe returning the flow to the laboratory sump (Figure 6).

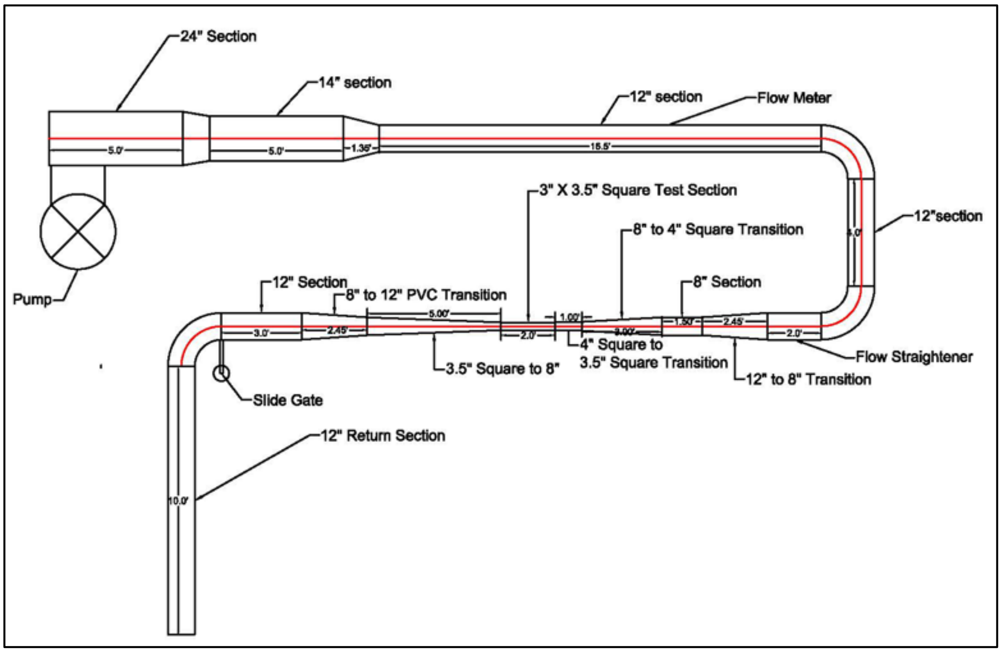

Figure 6 A schematic of the model layout.

Instrumentation

Uplift pressures were measured at pressure taps on the invert immediately upstream of the coating sample offset (under the unattached coating "flap") and the centerline of the side wall (Figure 7) using a ±15 psi Rosemount differential pressure transducer with accuracy of greater than 0.1% full span. Relative pressure was measured using a ±5 psi Omega pressure transducer with an accuracy of 0.25% full span.

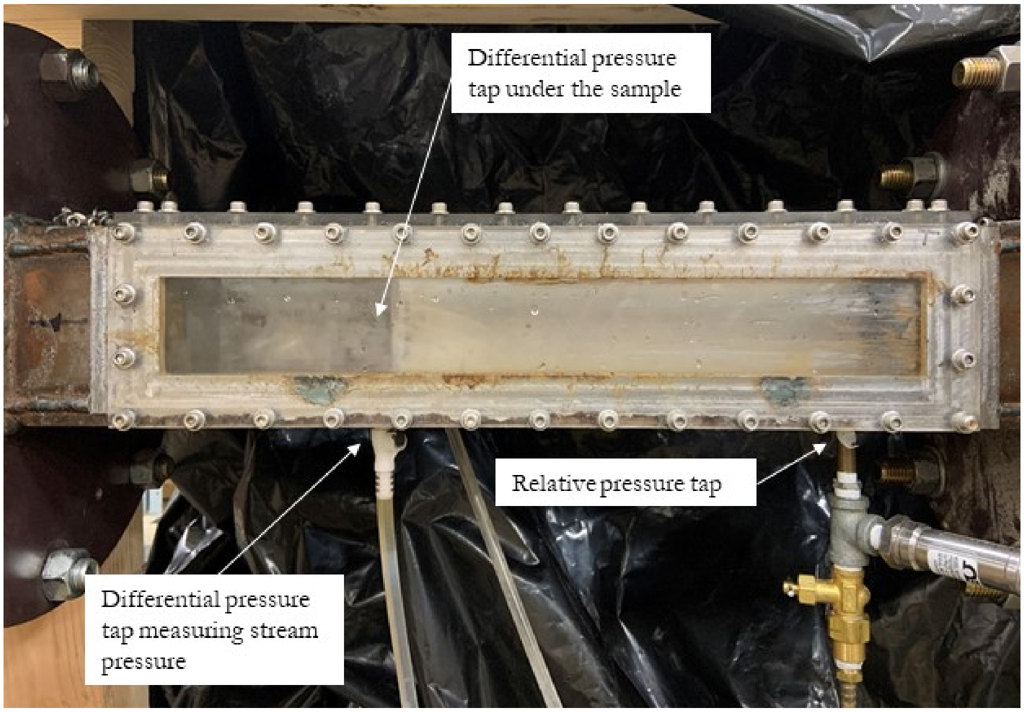

Figure 7 The test section with labeled pressure ports. The flow is from right to left.

The discharge was measured with a Siemens magnetic flow meter with an accuracy of ±0.25%. To prevent negative pressures within the test section, a 12-inch slide gate was installed downstream to control the back pressure within the test section. Test measurements were collected and recorded with an analog to digital converter hardware device and laptop computer.

Trial Coating Samples

Different coating systems were applied to mild steel plates machined to fit within the test section and expose the upstream edge of the coating to the approach flow. Polyurethane, Cavitation resistant lining, Polysiloxane, and Vinyl coatings were selected (Figure 8) and their average thicknesses were 71.3 mils, 52.0 mils, 13.0 mils, and 13.3 mils respectively. Due to the variability in coating thickness and surface finish, four to six samples of each coating type were prepared. To represent a discontinuity or initial point of failure (i.e. pipe joint or offset), a ¼-inch section was cut under the leading edge of the coating, referred to in this study as the “flap”. This process simulates the physical failure mechanism of the field observations where delamination started from a single defect point but spread significantly as the coating peeled off. Test samples with a traditional coal tar coating system were prepared with the intent for providing a baseline test for comparison but these samples were significantly damaged while preparing the steel plates which caused the coating to delaminate due to the heat from machining.

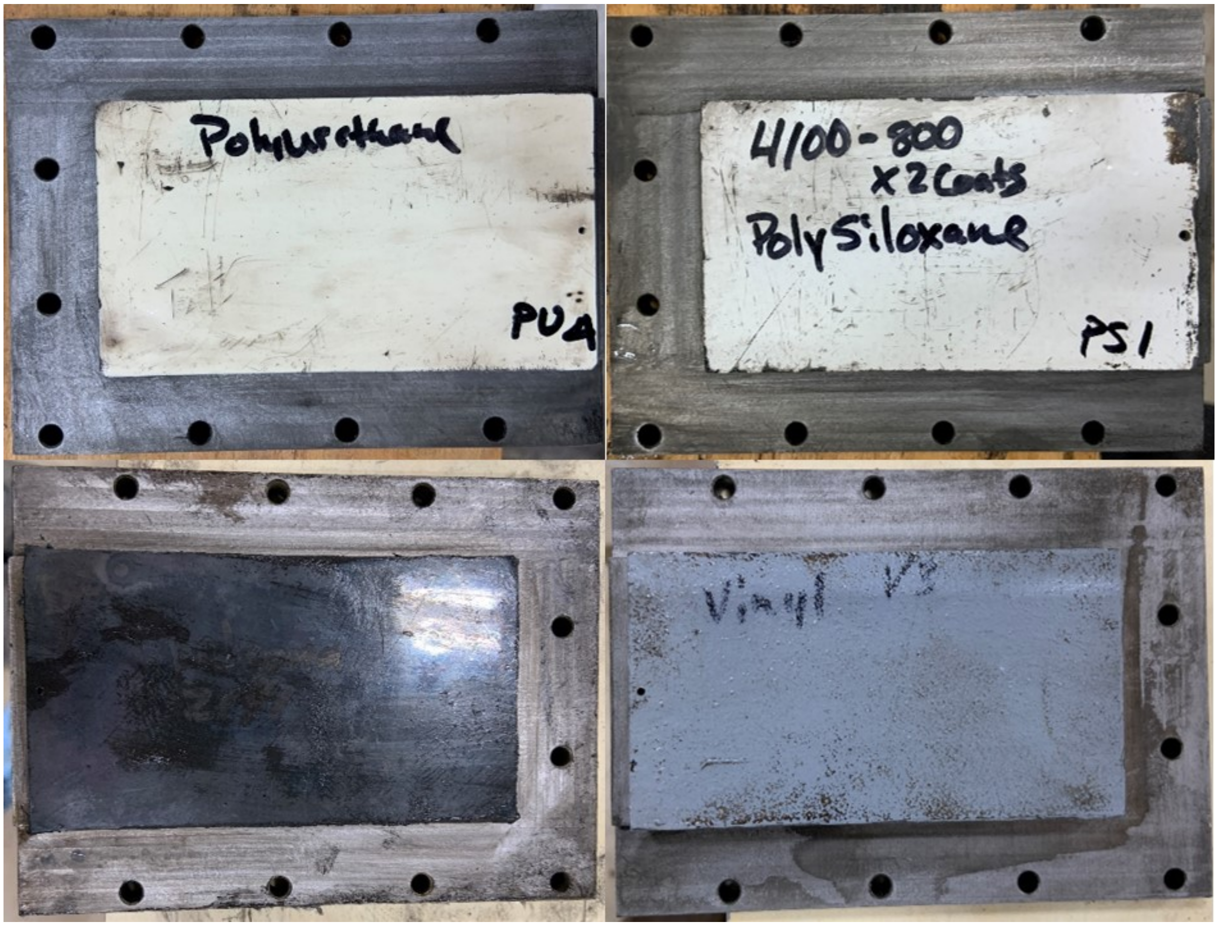

Figure 8 Top left, Polyurethane. Top right, Polysiloxane. Bottom left, Cavitation resistant lining. Bottom right, Vinyl.

The coating samples were subjected to approach flow velocities from 15 to 55 ft/s in increments of 10 ft/s at five minutes each until failure (Table 1). The maximum flow that the pumping system could deliver was 4 ft^3/s for a limited time due to limitations of the pumping. A more appropriate pump and pipping system will be available for future adhesion coating testing that can expand the range of approach velocities and exposure time.

Table 1 The testing matrix used to test coating systems to failure.

Discharge (ft^3/s)	1.1	1.83	2.56	3.29	4
Approach Velocity (ft/s)	15	25	35	45	55
Run Time at Each Setting	5 min	5 min	5 min	5 min	5 min

Trial Sample Test Results

Twelve trial coating samples were tested in the facility with the same test procedure. As shown in Table 2, only the Polyurethane coating failed under the conditions produced by the test facility. Due to issues with the existing pumping system the maximum approach velocity was limited to 55 ft/s and could not be held at that setting for more than five minutes. Polyurethane samples failed consistently in the range of 40-50 ft/s under different uplift pressures that were dependent on the extent the delaminated coating protruded into the flow field. Delamination generally began at the upstream corners of the coating and would extend downstream until the delaminated coating detached and was swept downstream. Post-test photographs are shown in Figure 9.

Cavitation resistant lining samples were also exposed to significant uplift pressures but initial delamination from the flap did not continue downstream nor fail. The other two thinner coatings, Vinyl and Polysiloxane, were also tested but did not fail. During the preparation process rather than creating a “flap” to initiate delamination coatings chipped away and did not have a similar initial failure point like the Polyurethane and Cavitation resistant lining samples.

*Table 2 The results of the preliminary coatings adhesion test. * Polyurethane 1 was also used for some of the shakedown testing which may have contributed to the low differential pressure at the point of failure.*

Coating System	Flow Velocity at Failure (ft/s)	Differential Pressure at Failure (psi)
Polyurethane 1	41.8	2.40*
Polyurethane 2	53.4	8.95
Polyurethane 3	52.3	10.16
Polyurethane 4	43.3	9.46
Polyurethane 5	44.8	6.06
Polyurethane 6	43.3	5.90
Cavitation resistant lining1-4	n/a	n/a
Vinyl 1	n/a	n/a
Polysiloxane 1	n/a	n/a

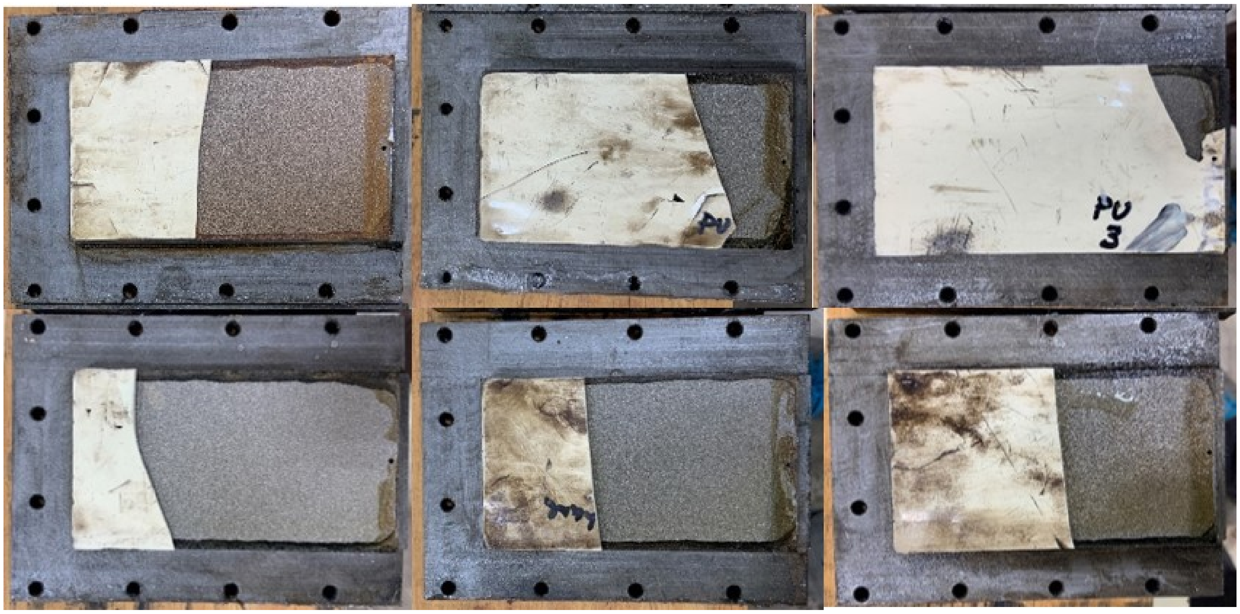

Figure 9 The six failed Polyurethane samples, increasing in sample number from left to right top to bottom. Polyurethane number three folded over from a corner and failed in a slightly different manor than the other five.

Polyurethane Trial Samples

Uplift pressure measurements were useful in further understanding the behavior of the Polyurethane coating samples during delamination and failure. Figure 10 shows an example time series of approach velocity and uplift pressure. The uplift pressure, which is measured using a pressure tap under the upstream flap, did not follow the velocity as expected until it exceeded 40 ft/s. This may have occurred because the flap was still covering the pressure tap near the center of the sample until the approach velocity was high enough to lift the flap at that location. The sudden spike and drop of uplift pressure indicate the point at which the coating was lifted into the flow and then detached, alleviating the uplift pressure.

A similar trend is shown for a different sample in Figure 11. However, at constant approach velocities of 35 and 45 ft/s the uplift pressure gradually increased which corresponds to visual observations of the coating slowly delaminating from the base plate. As delamination continued the extent that the upstream flap protruded into the flow field grew until failure finally occurred as shown by the sudden spike and drop in uplift pressure. The delamination and failure process of the Polyurethane samples is shown visually in Figures 12 through 14.

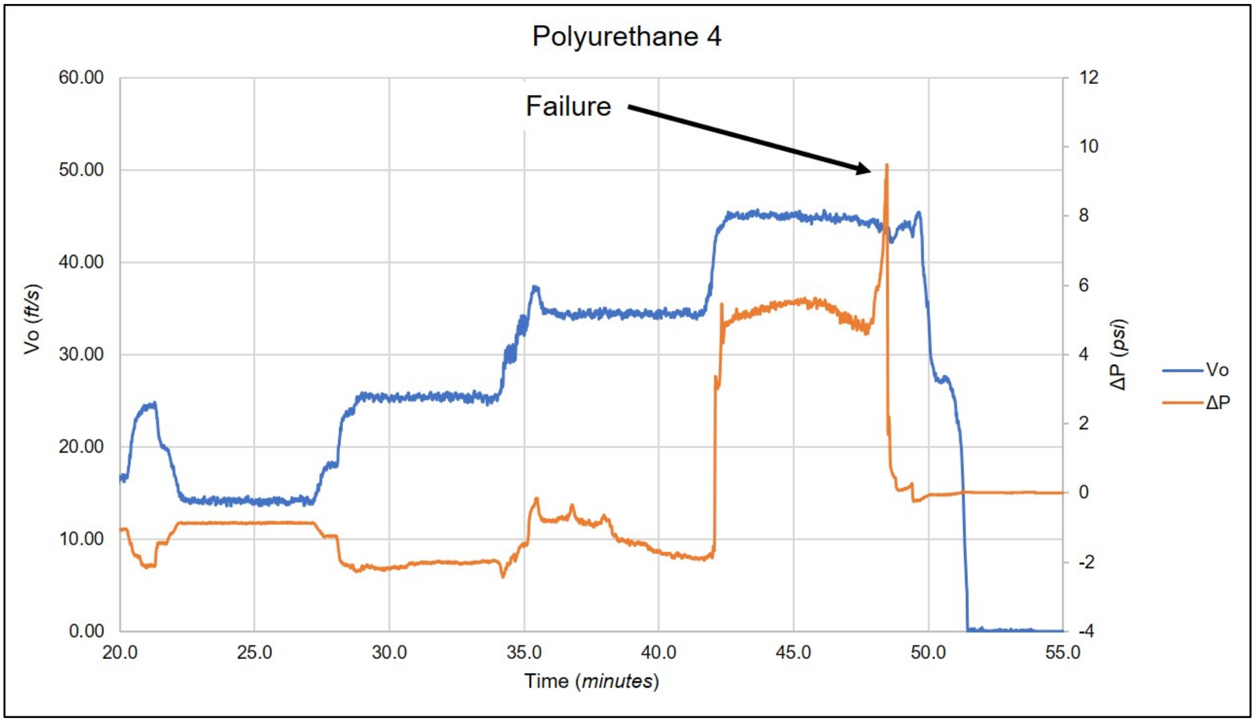

Figure 10 Time series approach velocity and uplift pressure acting on trial sample Polyurethane #4.

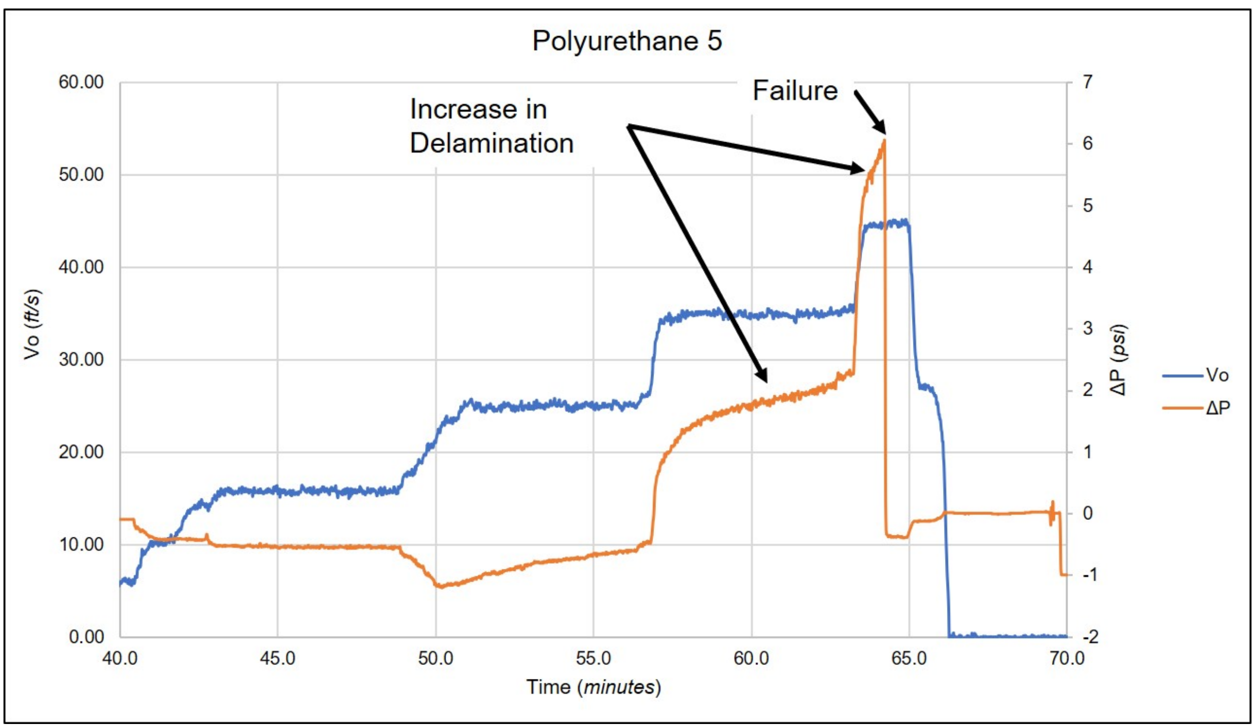

Figure 11 Time series approach velocity and uplift pressure acting on trial sample Polyurethane #5.

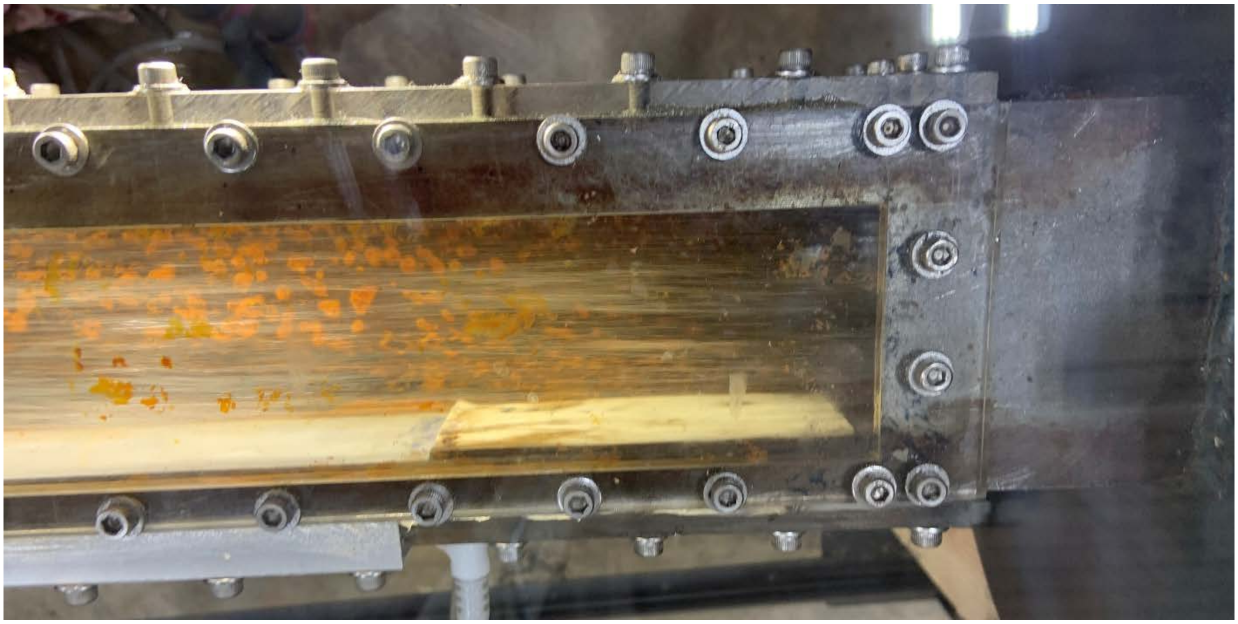

Figure 12 Photo of Polyurethane sample at low approach velocity. Flow is left to right.

Figure 13 Photo of Polyurethane sample at high approach velocity, delamination beginning at upstream corners of the coating. Flow is left to right.

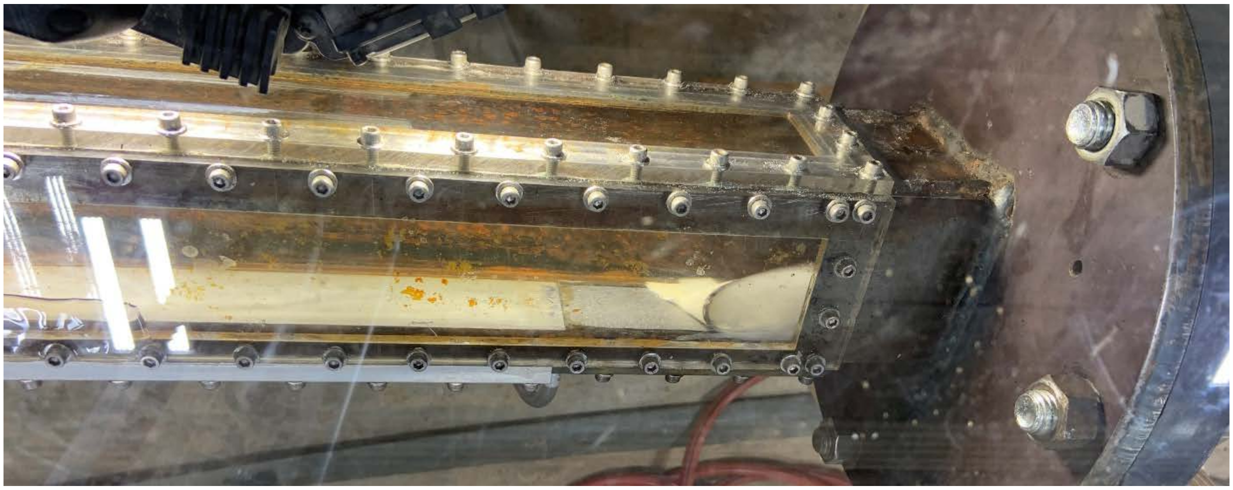

Figure 14 Photo of Polyurethane sample at high approach velocity, near complete failure. Flow is left to right.

Cavitation Resistant Lining Trial Samples

Test results of the Cavitation resistant lining samples showed better performance than the Polyurethane samples under the same test conditions without failure or any indications of delamination. Each sample was exposed to maximum uplift pressures of approximately 6 psi at approach velocities near 55 ft/s. Unfortunately, velocity profiles near the boundary were not able to be measured to compare calculated stagnation pressure with measured uplift pressure. The time series in Figure 15 shows that uplift pressures directly corresponded with approach velocities over the full range. Also, there was little variation in uplift pressure at each flow setting suggesting that gradual delamination did not occur. A longer exposure time at each setting in future tests would help confirm this finding. Visually, the upstream flap appeared to be very flexible (Figure 16) and not prone to cracking or detachment as seen with the Polyurethane coatings.

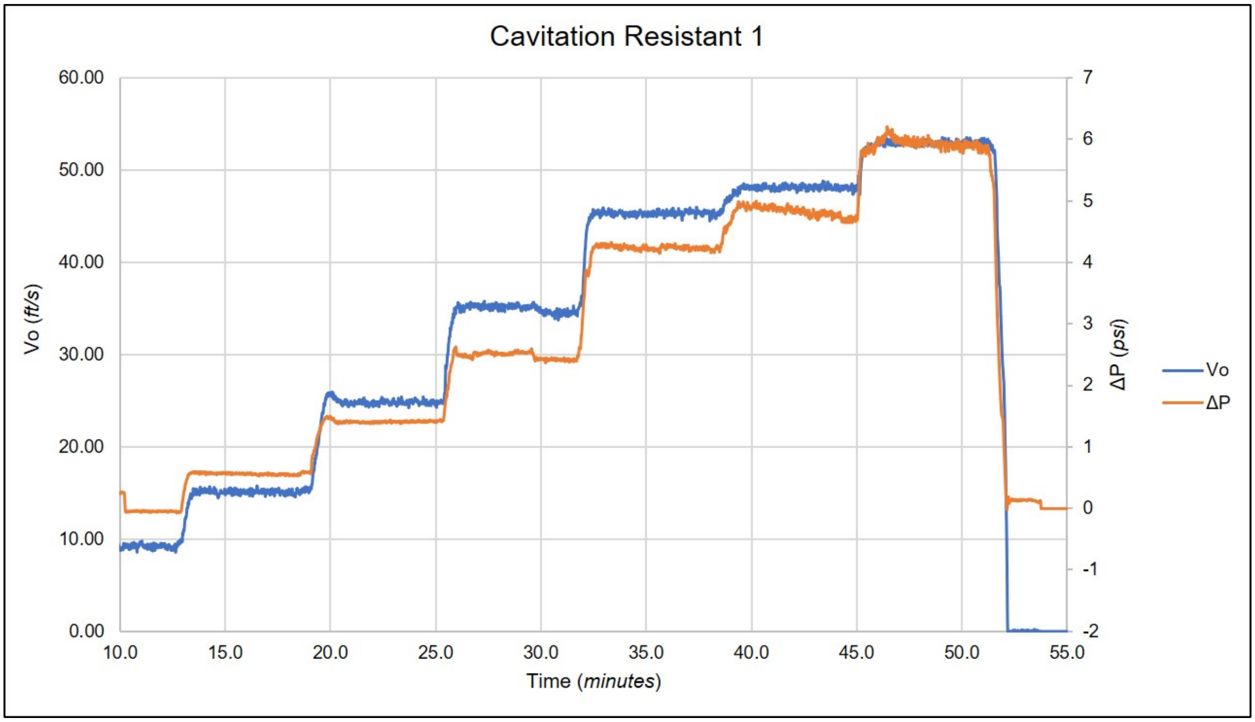

Figure 15 Time series approach velocity and uplift pressure acting on trial sample Cavitation resistant #1.

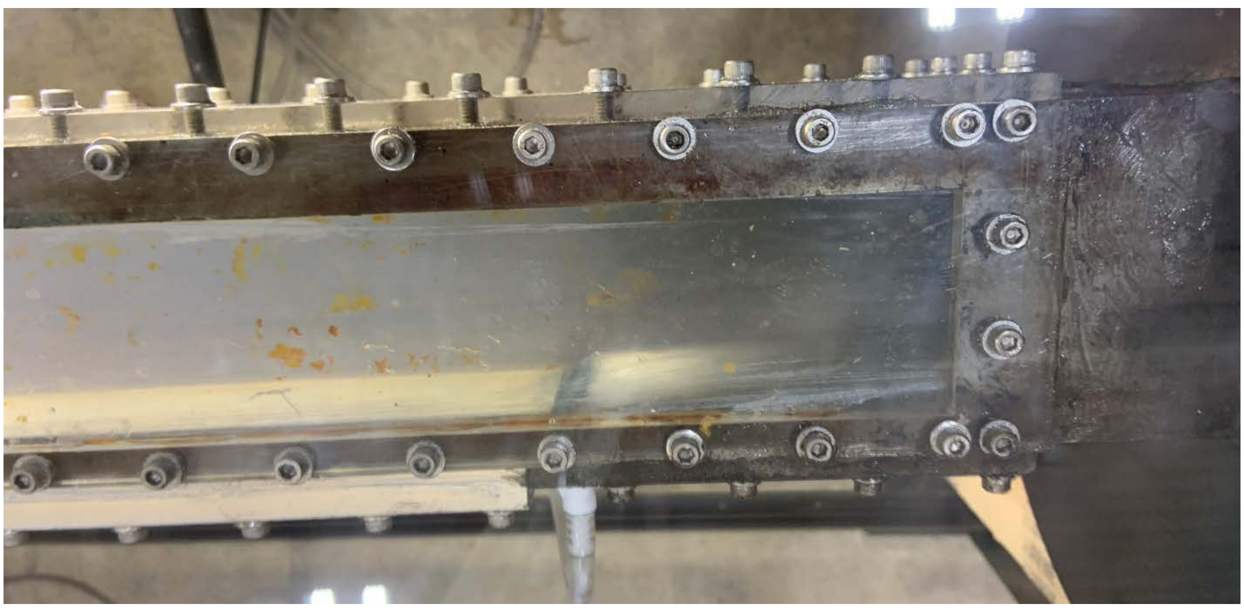

Figure 16 Photo of Cavitation resistant lining sample at high approach velocity. The upstream flap is bent backward and caused cavitation as seen by the white cloud of bubbles formed off the top edge of the coating flap. Flow is left to right.

Discussion – Application to the Field

Preliminary attempts have been made to compare laboratory results from the current test method with field data. To date recent field experience with coating delamination failures has been solely with Polyurethane coating systems. Operating conditions and coating thickness data were used to estimate uplift pressures for failures in conduits at Flatiron and Platoro dams (Figure 6). Operating data from Enders dam were not immediately available but may be for future analysis.

Failures in the laboratory occurred at higher uplift pressures and approach velocities compared to those in the field which could be due to several factors. First, actual uplift pressures were not measured in the field and ideal fully developed flow conditions were assumed to predict boundary layer velocities and stagnation pressures. More detailed analyses or numerical simulations may improve the accuracy of the fluid dynamics acting on the coating. Also, boundary layer velocities acting at the mid-height of the coating thickness were assumed in field uplift predictions. As shown in the laboratory tests the upstream edge of the Polyurethane coatings (same thickness in lab and field) would lift into the flow where it was exposed to higher velocities than those estimated at the coating mid-height. In some cases, the coating slowly peeled away, and the height of the upstream edge grew further increasing the measured uplift until the coating finally failed. A similar process likely happened in the field where the upstream edge of the coating lifted into the flow causing the actual uplift force to be significantly greater than what was predicted by the boundary layer velocity at the mid-height of the coating thickness.

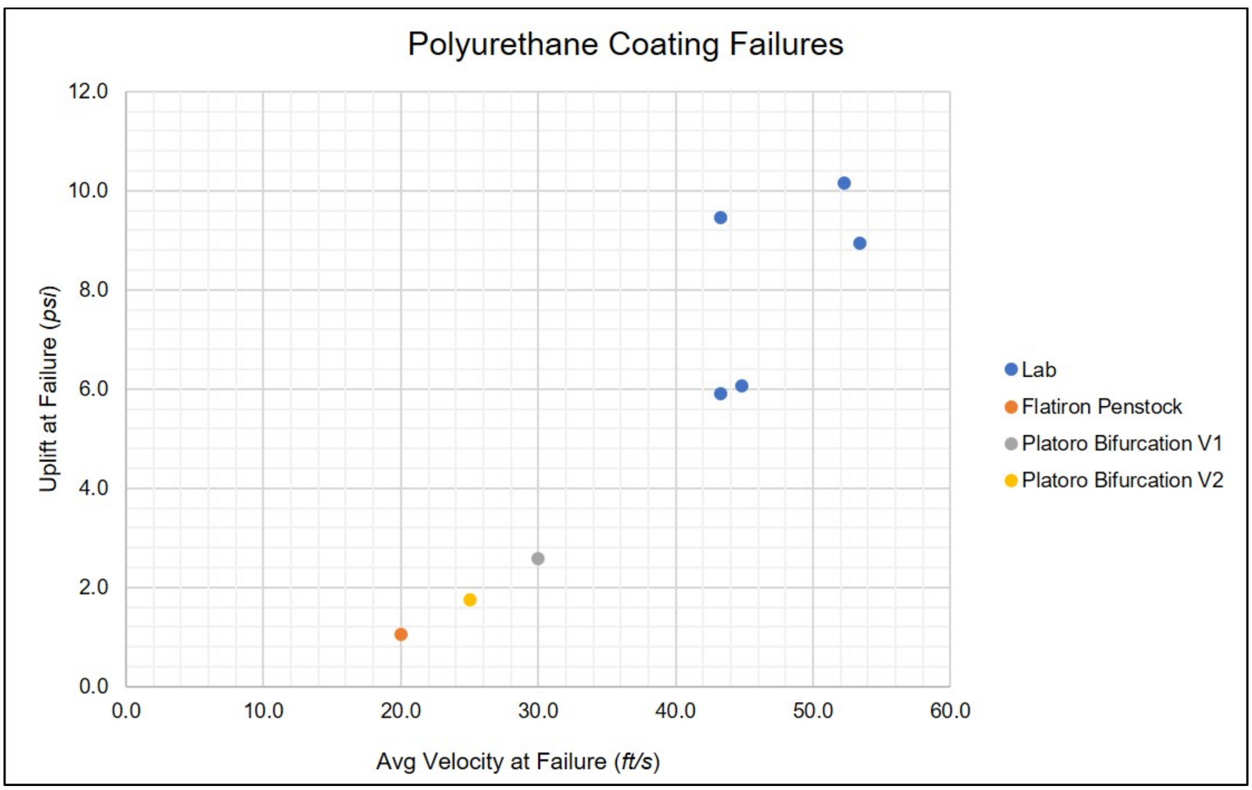

Figure 17 Comparison of uplift pressures at failures for laboratory and field case results from Flatiron and Platoro dams.

Other factors such as the extent of underlying corrosion and exposure time likely had an influence on field failure cases as well. To a large extent these factors are unknown and would be difficult to incorporate into a laboratory test method. However, the test method developed in this study could potentially be improved by increasing exposure times (within a practical range for laboratory testing) at each flow condition before increasing flow velocity. For example, many of the polyurethane examples failed as flow velocity was being increased to the next setting or soon after. Perhaps failures would have occurred at a lower velocity/uplift pressure had exposure times been increased. Modifications to the test method and further analysis of the field cases (exposure time, localized conditions, etc.) would likely improve the correlation between laboratory and field results and further validate the current test method for coating adhesion.

Conclusions and Recommendations

The objective of this study was to develop an improved test method for adhesion of coating systems that is more representative of field conditions. In this method, small representative coating samples are subjected to high discharge velocities to create uplift pressure that meet and exceed field conditions. The test method relies on creating stagnation pressure under the coating, or uplift force, sufficient to fail the coating system. The uplift force depends on the boundary layer velocity and coating thickness that protrudes into the flow field. This method utilizes direct measurements of the uplift force and approach velocity, coupled with visual observations, that help to describe the behavior and mode of failure of the coating sample.

Preliminary testing of this method used trial coating samples of Polyurethane, Cavitation resistant lining, Polysiloxane, and Vinyl coatings. Polyurethane samples failed within the test chamber and were compared to field case studies of coating failures in penstocks with the same coating system. Cavitation resistant lining samples did not fail due to a combination of high adhesion strength and coating flexibility. Polysiloxane and Vinyl samples did not fail due to difficulty in creating the upstream "flap" needed to initiate exposure to the uplift forces and need to be reconsidered for future testing. The following conclusions and recommendations should be considered for future adhesion testing with the current test facility and procedure.

- The test facility and procedure developed in Reclamation's Hydraulics Laboratory successfully simulated field-scale approach velocities and uplift forces to fail coating systems by delamination. The test method could be improved by increasing the upper limit of approach velocities within the test chamber and increasing the exposure time of each flow condition.
- Some coatings could not be tested due to difficulty in creating the upstream "flap" (coating not adhered to base material) needed to initiate coating failure. The upstream "flap" should be created as part of the coating application process rather than cutting or machining it on the metal test sample after it has already been coated. This is especially true for thin coatings (≈15-20 mils) and coatings that are sensitive to heat such as coal tar.
- For Polyurethane coatings, test results from the laboratory showed a greater uplift pressure required for failure compared to coating failures in the field. This may be due to several factors including unknown localized hydraulic conditions acting on the field coating, the amount of underlying corrosion, and the extent that the upstream edge of the coating defect was lifted into the flow. While all these factors cannot be accounted for in a laboratory test, further investigation into the hydraulic conditions of failures in the field will likely improve the correlation of laboratory testing and field experience.

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Data

Data identified for the creation of this project are available upon request.
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- Short description of the data: hydraulic calculations and measurements
- <1MB of data