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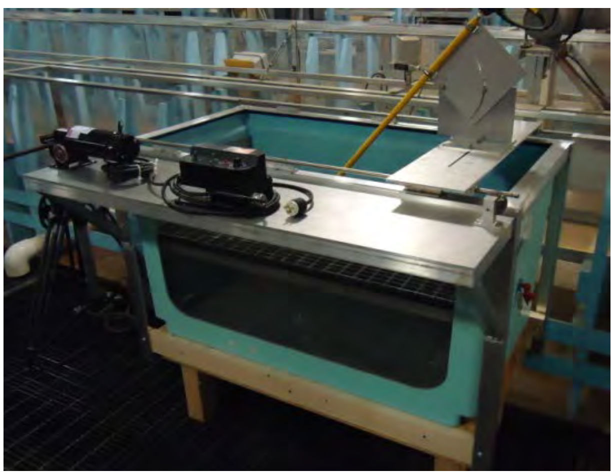
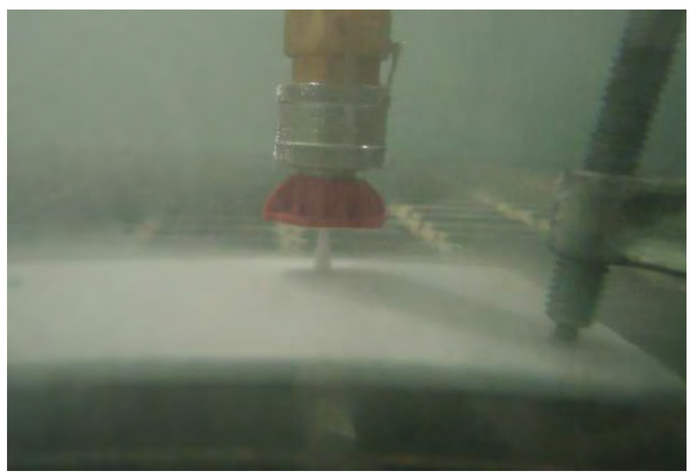
Resistance of Protective Coatings to High Pressure Water Jets for Invasive Mussel Removal

Research and Development Office





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Bureau of Reclamation
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Resistance of Protective Coatings to High Pressure Water Jets for Invasive Mussel Removal

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

Acknowledgments

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Disclaimer

The information provided in this report is believed to be appropriate and accurate for the specific purposes described herein, but users bear all responsibility for exercising sound engineering judgment in its application, especially to situations different from those studied. References to commercial products do not imply endorsement by the Bureau of Reclamation and may not be used for advertising or promotional purposes.

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Introduction

Invasive mussels were introduced to the United States in the early 1980's. Zebra mussels (*Dreissena polymorpha*) have invaded much of the eastern portion of the country and have appeared in locations throughout the mid-west and western United States. More recently, quagga mussels (*Dreissena bugensis*) have colonized in Reclamation facilities on the Lower Colorado River and other locations throughout the West (Reclamation, 2009). These invasive mussels cause many problems including increased head differential across trashracks, increased debris from aquatic weeds, fouling of equipment, decreased water flow through piping systems, and clogging from mussel shell debris. Many of these problems may be reduced through the development of new technology or using existing technology in new ways.

Protective coatings are an existing technology used for environmental mitigation. Reclamation's Materials and Engineering Research Laboratory (MERL) has been actively testing experimental and commercially available coatings which aim to reduce mussel settlement on hydraulic structures and equipment. In particular, MERL's test program has focused extensively on foul release coatings which do not contain a biocide. Foul release coatings deter attachment of fouling organisms using surface chemistry to significantly weaken the potential chemical bond between the organism and the substrate. Laboratory and field testing has determined that effectiveness of foul release coatings is typically undermined by attempts to increase durability. So called durable foul release coatings appear to have weaker attachment by mussels compared to conventional coatings but are still unable to resist colonization. The effectiveness of these coatings may be enhanced by using them in conjunction with water jetting for removing attached mussels. Though submerged water jetting is not new, its effectiveness on and impacts to coatings are unknown. Testing in this study will help determine the operational limits and effectiveness of submerged jetting to remove mussels from coatings.

The main objective of this research is to determine the limits of water jetting operation to remove attached mussels from coatings without causing damage. The goal of this study is to find an operational range for jetting that is both effective and safe that can then be applied to future applications which utilize foul release coatings and water jetting systems together. To accomplish this objective, a test procedure was developed to identify jetting limits of mussel removal and durability for specific coatings and materials. Various existing and newly developed coating systems were subjected to the test procedure in both the laboratory (durability/damage) and the field (live mussel detachment) to determine the optimal operating range for each coating. Measurable hydraulic parameters can then be used to design a jetting system to operate within the effective range potentially saving costs by reducing pumping required for jet flow and avoiding coating damage.

Literature Review

Several sources were consulted on water jetting as it pertains to impact material durability and removal of invasive species. Various books, journal articles, and reports were searched for jetting related topics including existing test procedures and standards, jetting for mussel removal, and hydraulic parameters of submerged jets. To date water jetting processes for mussel removal have been mostly trial and error. However, much was learned about hydraulic parameters of submerged jets as they relate to water jetting for mussel removal. A summary of all reviewed literature is presented in Table 7 of Appendix A.

High Pressure Jetting for Mussel Removal

Reclamation (2010) used a high pressure jet to remove mussels from inside an intake pipe at Davis dam. A rotating jet nozzle was inserted into a submerged pipe that had been heavily colonized with mussels. The jet was operated at pump pressures up to 10,000 psi and successfully removed the mussels from the pipe walls. However, underwater video revealed areas where coating material was also removed as well as areas where some biofouling remained. If the optimum operating criteria were known, jetting possibly could have removed mussels without further damage to the coating or lining.

In a study on zebra mussels, Ackerman *et al* (1995) used a submerged jet almost parallel to the boundary to study mussel adhesion to various surfaces. A single mussel attached to the surface was exposed to flow velocities up to 24.6 ft/s to determine adhesion strength based on a unique detachment parameter. Their results showed large variation among surface types as well as failure mechanisms. Observations showed that the mussels would orient themselves with the flow until velocities were sufficient to cause failure of either the byssal pad, byssal thread, or the connection of the byssal stem with the body. The difference in failure mechanisms may be a reason for adhesion strength to vary with substrate type.

The U.S. Army Corps of Engineers have used water jetting to remove zebra mussels from concrete surfaces (US Army Corps of Engineers). They recommend operating (pump) pressures of 4,000 psi to 10,000 psi for mussel removal. They also point out that the distance from the nozzle to the surface is a very important parameter for this method. It is not specified whether or not the jetting was submerged. Other sources recommend pump pressures greater than 3,000 psi for unsubmerged surfaces and to remove byssal threads left behind by the mussels (Mackie & Claudi, 2010).

Rather than using pump pressure, the current study focuses on impact pressure at the boundary as the main parameter. Impact pressure, which is expected to directly affect cleaning effectiveness and durability, is dependent on a number of variables including pump pressure, orifice size, standoff distance, jet shape and impingement angle. If the correct impact pressure range is known then it can be used to design the remaining components of the jetting system.

Test Procedures

Standards and methods were found that test biological performance of various surface materials. The Florida Institute of Technology (2011) developed ASTM standards and test methods for assessing the physical condition of coatings w/ biofouling as well as measuring adhesion of hard fouling organisms. They also developed a method of testing adhesion strength of biofilms to a surface using a water jet. These standards and test procedures are more applicable to the removal testing of this research which assesses the limits of mussel release from coatings with water jetting.

An ASTM standard (G134-95, 2010) describes a test procedure that uses a submerged cavitating jet to quantify material durability which is very similar to testing performed in the current study. However, the goal of the current testing was to find durability of coatings which are more likely to be damaged by impact pressure of the impinging jet rather than prolonged cavitation on the surface.

One source reported a test procedure for predicting erodibility of soils (Hanson & Cook, 2004). Their testing used a submerged jet impinging on a cylindrical-shaped soil sample to predict the soil erosion rate. Soil stress was estimated using theoretical equations. Even though their testing focused on erosion rate instead of incipient damage like the current study, some of their theory and analysis methods may still be applicable.

Hydrodynamics of Submerged Jets

Various journal articles pertaining to hydrodynamics of submerged jets were reviewed to better understand the parameters that may affect coating durability as well as mussel removal. Albertson *et al* (1948) discussed separate flow zones of a submerged jet. The zone of flow establishment (core length) is the distance from the exit to where the centerline velocity is begins to vary as shown in Figure 1. Within this region, the diffusion region of the jet with the ambient fluid has not yet reached the center line of the jet which allows the jet velocity to remain unchanged. Test results indicated that the core length is approximately 6 times the orifice diameter when using a circular jet. Once the diffusion region has encroached upon the center line, jet velocities begin to decrease with distance from the exit. Fluid behaviors within these zones are of interest for coatings since durability and mussel detachment will be affected by velocity and distance. Resulting parameters such as pressure and shear stress need to be quantified to develop water jet operating criteria for specific coatings. Cavitation may also be an issue for coating durability due to the formation of eddies and the pressure drop that results from the diffusion of a high velocity jet.

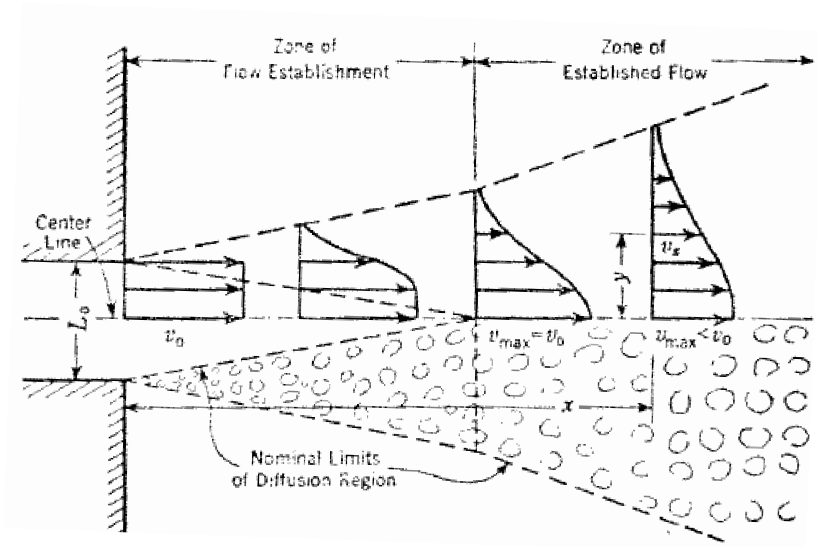

Figure 1 Schematic showing zones of submerged jet flow, from Albertson *et al* (1948)

Hanson *et al* (1990) made physical measurements of pressure and stress distributions of a submerged circular jet on a planar boundary. They used a temperature compensated pressure transducer to measure pressure and a hot film sensor to measure shear stress at a boundary which was oriented perpendicular to the direction of the jet. In their experiment, jet velocity varied while nozzle distance from the boundary was constant. No measurements were made within the core length of the jet. Their data correlated well with previously developed pressure and stress equations for submerged jets. Equation 1, a semi-empirical equation originally developed by Beltaos & Rajaratnam (1974), predicts the peak pressure at the center of a jet normal to the boundary. Maximum shear stress of the jet on the boundary is predicted using Equation 2. While these equations predict parameters at a boundary that are important for water jetting for mussel removal they cannot be applied to high-velocity jets where cavitation may occur similar to jets used in the current study.

$$P_s = C_P\left(\frac{\rho {U_0}^2}{{H/_d}^2}\right) \tag{1}$$

$$\tau_{om} = C_\tau\left(\frac{\rho {U_0}^2}{{H/_d}^2}\right)^n \tag{2}$$

Where: $C_P = 30.2$
ρ = density of water
U_0 = velocity of jet at orifice
H = distance from the orifice to the boundary
d = orifice diameter
$C_\tau = 0.205$ (English units)
$n = 0.74$

Experimental Methods

Methods of this study focus on impact pressure of the impinging jet on the coated boundary as the main parameter for both durability and mussel removal. Impact pressure is dependent on measurable hydraulic parameters such as nominal jet velocity (velocity at nozzle orifice), orifice diameter, nozzle distance from boundary, jet angle, and jet shape (circular or fanned). Tests were performed to determine the minimum impact pressure required to remove mussels and the maximum pressures allowed before damage occurs for various coating types. This pressure range can be determined and then used in conjunction with appropriate hydraulic parameters for water jetting system design. This study targets controlled water jetting systems that are submerged and automatically operated rather than manual wash systems.

Coatings and Materials

A range of coating and material types were chosen for testing to obtain results for both existing coatings common throughout Reclamation as well as recently developed foul release coatings for mussel control. Table 1 shows the 15 different coatings and materials subjected to the test procedure. As shown, all coatings were tested for both durability and mussel release with the exception of Fuji Smart Surface and two experimental coatings. Fuji was not subjected to the release test because there were no mussels attached to the surface and the experimental coatings were not present at the field site.

Table 1 Coatings and coating types used for laboratory testing.

Coating Type	Coating	Damage	Release	Notes
Conventional	Duraplate 235	x	x	Solvent-borne two component polyamide epoxy manufactured by Sherwin Williams
	Coal Tar Enamel	x	x	Coal Tar Enamel and primer system applied by Lonestar Specialty Inc.
	Tar Guard	x	x	Coal Tar Epoxy by Sherwin Williams
	Amercoat 240	x	x	Solvent-borne two component polyamide epoxy manufactured by PPG
Foul Release	HPL-2510FR	x	x	Silicone-epoxy hybrid system by Duromar
	Seaspeed V5	x	x	Silicone-epoxy hybrid system by SeaCoat
	Trunano	x	x	Blue Planet Nano active surface foul release coating
	Intersleek 970	x	x	International Fluorinated silicone foul release coating

	Rylar Experimental FR coating	x	x	RylarSingle component proprietary foul release coating
	Fuji	x		Smart surface silicone (white & black)
Experimental	1420 PFA	x		FR (MERL)
	R3	x		FR (MERL)
Uncoated	Galvanized Steel	x	x	
	Stainless Steel	x	x	

Test Apparatus

A 120 gallon tank was used as the main structure of the test apparatus. Figure 2 shows the features of the test tank which include a side window to view testing. A sample coating plate was clamped to the grate beneath a submerged water jetting nozzle attached to a high pressure wand. The wand was mounted above the tank so that its position and angle could be adjusted to any horizontal or vertical location within the tank. The mount was attached to linear motion shafts and a belt and pulley system controlled by a variable speed motor. This system allowed coatings to be tested with either a stationary or traveling water jet at a controlled speed.

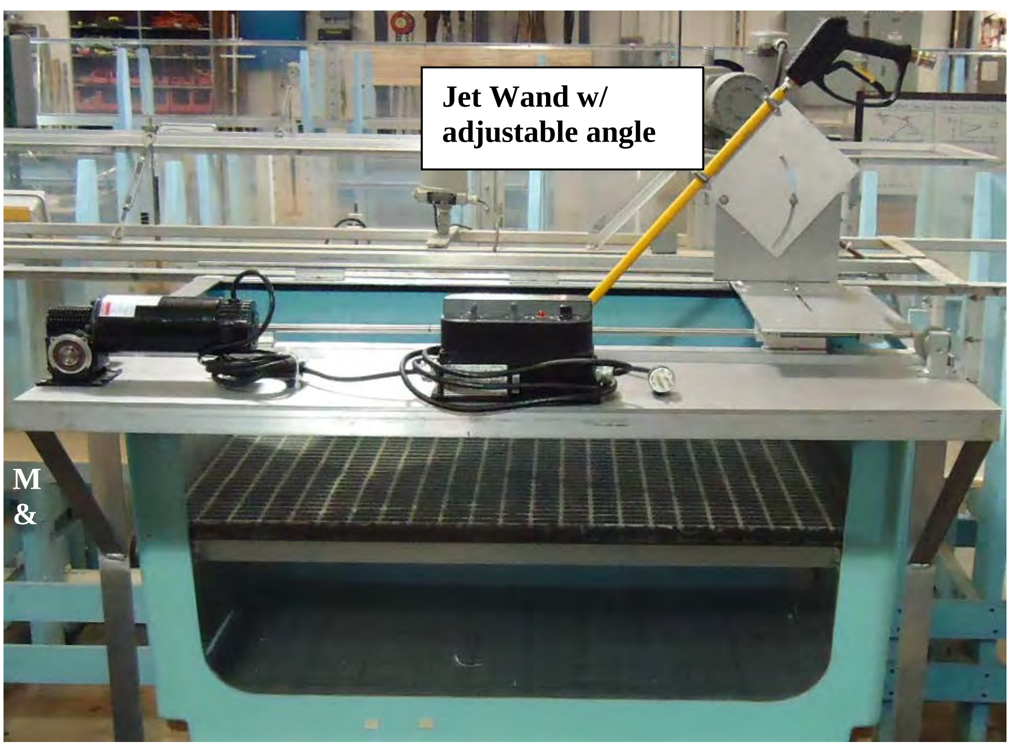

Figure 2 Test apparatus used for coating durability and mussel release testing in both the laboratory and the field.

Water was supplied to the wand and nozzle by a 2 HP Landa pressure pump (Figure 3) at flows and pressures up to 2.8 gpm and 1,000 psi respectively. The pump required a 120V power outlet and a water supply from a garden hose type attachment which was simple to setup and operate at a field test site. Figure 3 also shows a pressure gage used to measure pump pressures during testing. A 10 HP pump became available later in the study and was used for some of the impact pressure testing in the lab. Jet velocities were estimated with the continuity equation using measured flow and orifice area. Flows were measured upstream of the pressure washer using a model F-1000 inline Blue-White propeller meter with an accuracy of ±2% (Figure 4).

Figure 3 Landa pressure pump used to create water jets for coatings testing.

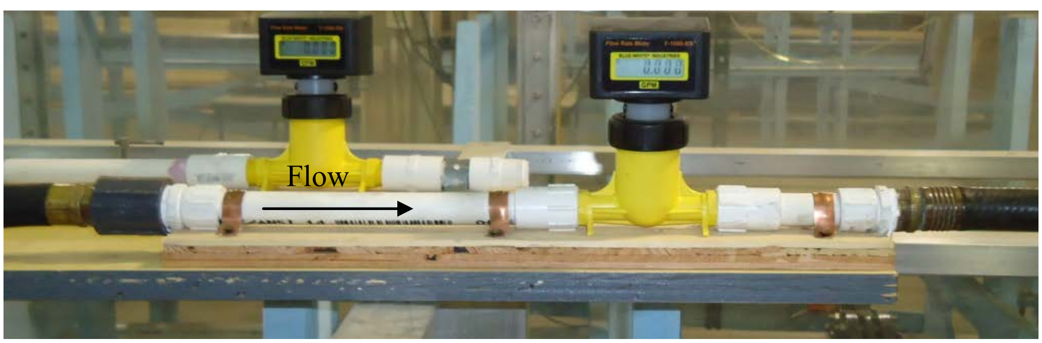

Figure 4 Inline propeller flow meter used to measure flow and estimate nozzle jet velocity.

Impact Pressure Testing

To quantify jet effects on coatings and attached mussels it was necessary to define how the boundary impact pressure of the impinging jet varies with jet distance and velocity. Impact pressure testing was not part of the original project plan due to the assumption that the equations by Hanson *et al* (1990) could be used. Initial durability testing showed that Hanson's equations were not applicable to water jet cleaning in the current study due to the high velocities and heavy cavitation. Impact pressure testing was performed to define the relationship between pressure and jet hydraulics (distance and velocity) for both a spot jet normal to the boundary and a 40° fan jet at 45° to the boundary used for durability and removal testing respectively.

To predict impact pressures from submerged cavitating jets, measurements were made on a flat plate using a piezometric dynamic pressure transducer (Figure 5). Table 2 provides information for the transducer and settings used during testing. A sensitivity analysis showed that a high acquisition frequency was needed to capture the rapid pressure fluctuations caused by cavitation. However, a short sample time period (2 seconds) was sufficient. Also, the Root Mean Square (RMS) of the measurements was used to quantify the magnitude pressure of each test due to the large variation of positive and negative pressures.

Table 2 Technical information of the transducer and data acquisition settings used for pressure measurements.

Make/Model	Kistler, Model 211B1
Size	Diameter = 0.25 inches
Frequency	50 kHz
No. Samples	100,000
Range	10,000 psi
Resolution	0.1 psi (rms)

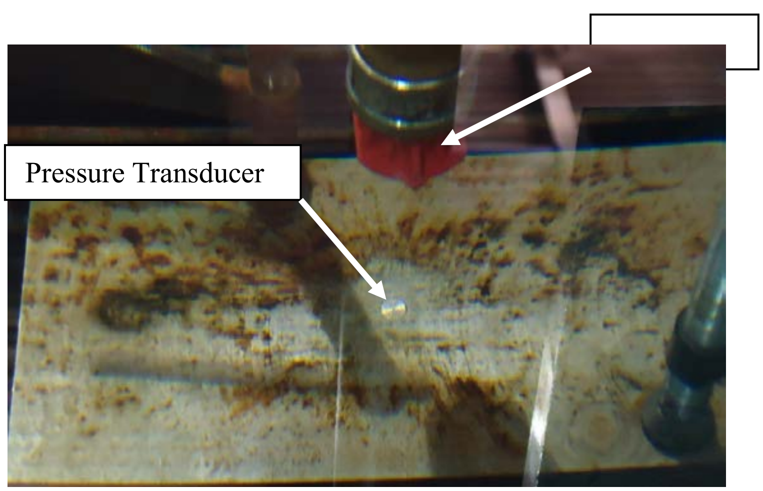

Figure 5 Piezometric pressure transducer set flush with the surface boundary used for impact pressure testing.

Damage Pressure Testing

Coating durability was assessed by measuring the hydraulic parameters of the impinging jet (nozzle distance, orifice diameter, and jet velocity) present when damage first occurs on the coating surface. All durability testing was performed using the test apparatus in Reclamation's Hydraulics Laboratory in Denver, CO.

Test Procedure

The durability test procedure was designed to target parameters likely to remain constant in a prototype water jetting system as well as provide conservative results. The test procedure given in Table 3 used a stationary spot jet (circular, 0° Fan) nozzle with an orifice diameter of 0.06 inches that concentrated the impinging jet over a single location throughout the test period. The jet was held perpendicular to the boundary. While a stationary spot jet would not likely be used in a prototype application, it does provide coating durability information that is conservative for typical water jetting applications.

Table 3 Steps for Test Procedure for durability testing.

Test Procedure for Durability of Protective Coatings using Stationary Water Jetting	
1	Select nozzle type (spot jet) and size (orifice diameter) and jet velocity to remain constant throughout test
2	Set distance from top of sample plate to nozzle tip (jet distance H, typically start at 3 inches)
3	Run jetting test for set time period (3 minutes)
4	Turn off jet and inspect plate for any visual damage
5	Set distance to next increment (usually 1/2 inch closer) and repeat test
6	Continue testing at decreasing distances until any damage on plate is visually apparent
7	If no damage is apparent run jet for 1 hr to determine if time is a variable.
8	Turn off jet and inspect plate for any visual damage

For durability testing time was held constant while nozzle distance to the surface (H) varied (Figure 6). While time does affect test results, distance and velocity were chosen as variables because they will likely be the design variables in a prototype application where the jet nozzle will be traveling along the surface. Due to the traveling motion of the jet time will become less of a factor for durability.

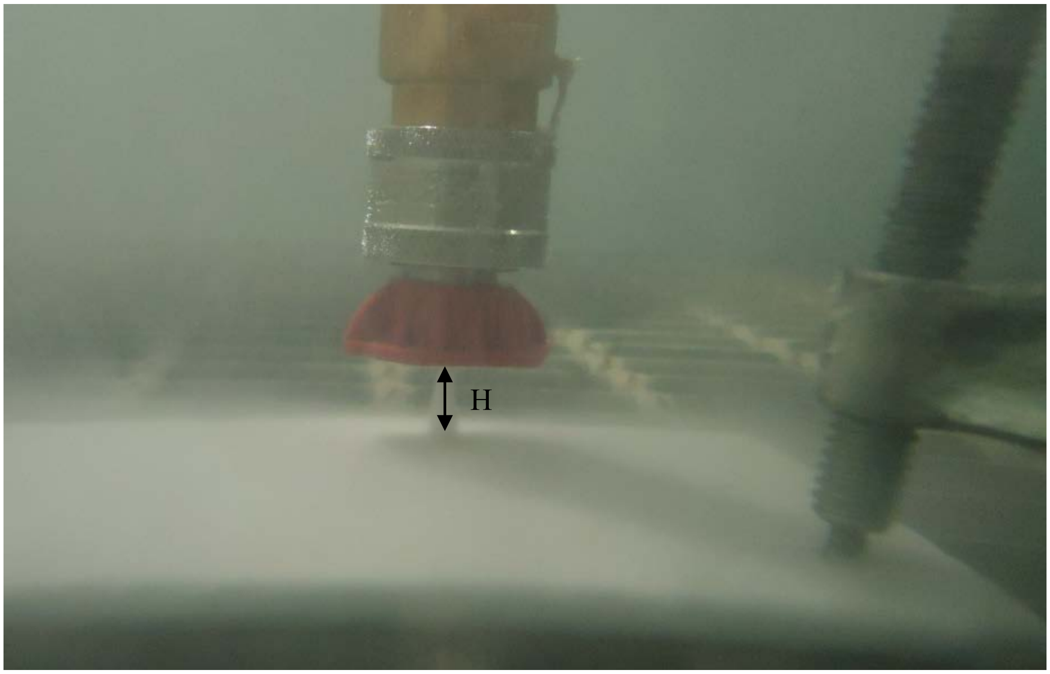

Figure 6 Spot jet used for durability pressure testing.

Release Pressure Testing

Testing for mussel removal was performed at Parker Dam near Lake Havasu City, AZ where live quagga mussels were attached to the coatings. Plates were coated and submerged near the upstream face of the dam where they remained for several months to allow adequate mussel settlement. Field tests have shown that that highest settlement typically occurs in summer months. Therefore, it is desirable to test coatings in late summer or early fall after at least 2-3 months of immersion (Reclamation, 2012). The same test apparatus used for durability testing in the laboratory was taken to the field for removal testing (Figure 7). TSC researchers made two different trips to Parker Dam for testing. Initial testing was performed the beginning of December 2011 and additional tests the middle of July 2012 after the respective fall and spring mussel breeding seasons. This also allowed testing of mussel removal at two drastically different water temperatures (average of 65.1°F in December and 98.2°F in July).


Figure 7 Test apparatus used for initial mussel removal testing at Parker Dam December 2011.

Test Procedure

The test procedure for mussel removal shown in Table 4 created test conditions more likely to be found in an actual prototype application. A 40° fan jet with an orifice diameter of 0.06 inches was used to cover a wider section of the surface. The jet was set at a 45° angle to the surface to create additional shear stress on the attached mussels (Figure 8). Also, the jet travelled along the boundary at a constant speed of 0.5 inch per second. The same hydraulic parameters (nozzle distance and velocity) used for durability testing were measured at the time when all mussels were removed from the coating. Tests were documented with photographs and videos.

Table 4 Steps for Test Procedure for mussel release testing.

Test Procedure for Mussel Detachment using Water Jetting	
1	Select jet angle, distance, nozzle type (fan angle) and travel speed to remain constant throughout test.
2	Set jet velocity to lowest setting, making 1 pass across mussel-laden test sample. Inspect sample for remaining mussels/byssal threads/coating damage.
3	**If mussels/byssal threads remain (1st Run Only)**: Increase jet velocity and repeat step 2 over untouched portion of the test sample.
4	**If mussels/byssal threads were removed or if coating was damaged (1st Run Only)**: Increase distance and repeat step 2 over untouched portion of the test sample.
5	Continue increasing velocity/decreasing distance until sample is sufficiently clean or until jetting limits have been reached.

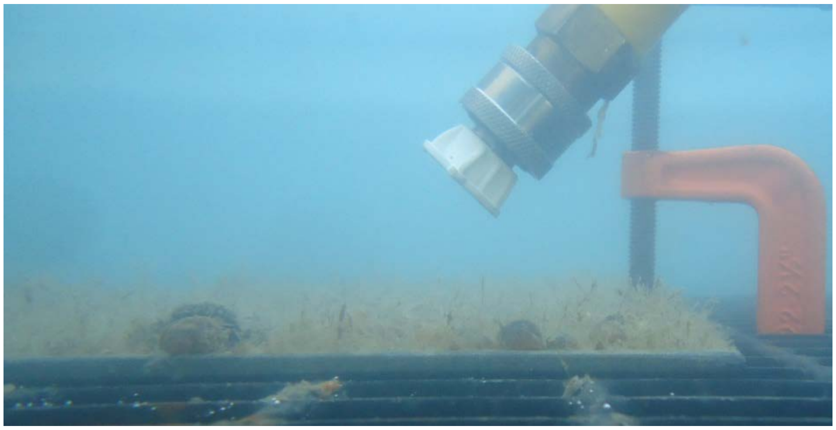

Figure 8 40° fan jet at a 45° angle used for release pressure testing in field tests with live quagga mussels.

Results and Discussion

Impact Pressure Testing

Impact pressure tests were performed for both a spot jet set perpendicular to the boundary and a fan jet with a 40° fan set at a 45° angle to the boundary, both with a 0.06 inch orifice. The equations developed from impact pressure tests define the relationship of impact pressure at the boundary to nozzle distance and jet velocity for the same range of operation used in both durability and removal testing. If an extended range of hydraulic parameters is required for prototype applications (i.e. higher jet velocity or greater distance), additional impact pressure tests may be necessary to obtain accurate results for the extended range.

Circular (Spot) Jet – Durability

Figure 9 shows data from spot jet testing used to form Equation 3. This equation was used to predict damage pressures for durability testing and is valid for a distance range of 0.75 – 5 inches and a velocity range of 190 – 280 ft/s. Due to the tight concentration of the spot jet, pressures were sensitive to velocity as well as distance. While equation 3 predicts the RMS pressure it should be noted that pressures greater than 300 psi were detected due to the intense cavitation implosions near the boundary.

Tests at distances less than 0.75 inches produced pressure results that were not consistent with the trend shown in Figure 9. For this case damage and release pressure results are reported as 30 psi because the true value is not known but is not greater than 30 psi. The cause is not known but may be due to this distance being a transition of flow establishment zones discussed previously by Albertson *et al* (1948) (Figure 1). The transition from one zone to the other may affect the amount of cavitation implosions on the pressure transducer. However, for all practical purposes, the equations provided by the impact pressure results are reliable and adequate for the necessary limits of durability and release testing.

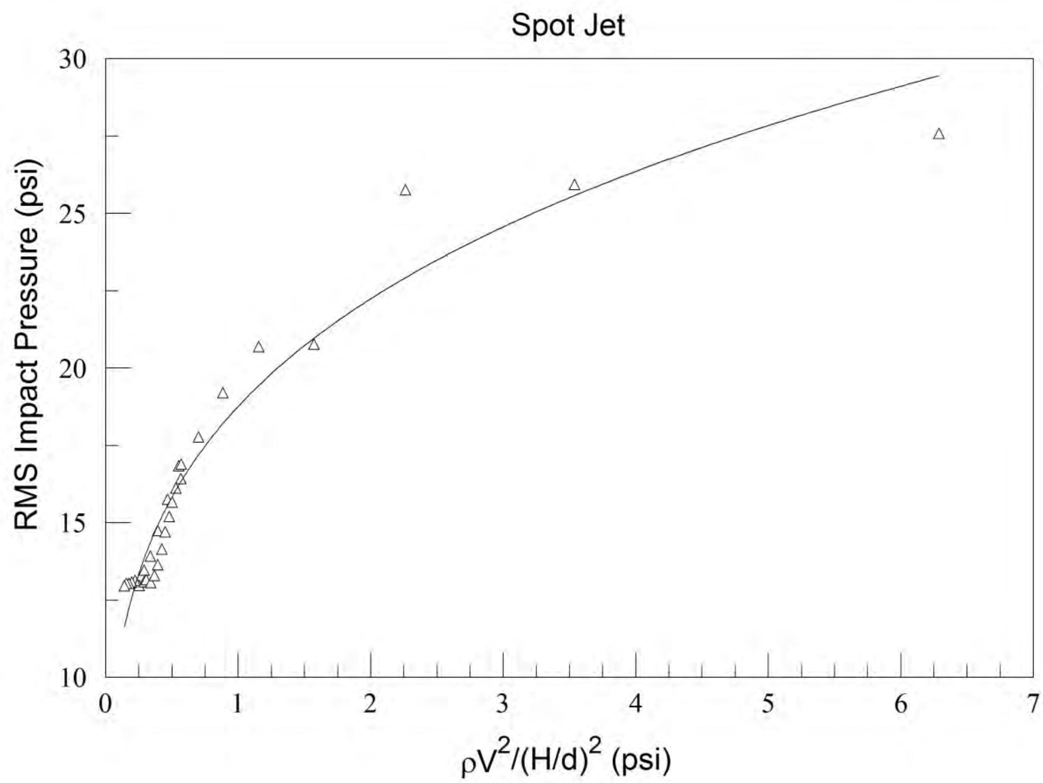

Figure 9 Impact pressure results for a spot jet set perpendicular to the surface for durability testing. For this data set $R^2 = 0.943$.

$$P_{spotjet} = C\left[\frac{\rho V^2}{\left(\frac{H}{d}\right)^2}\right]^n \qquad (3)$$

Where: C = 18.768

ρ = density ($slugs/ft^3$)

V = velocity (ft/s)

H = nozzle distance from surface (inch)

d = nozzle diameter (inch)

n = 0.245

Fan Jet – Release

Figure 10 shows data from the fan jet tests used to form Equation 4 which was used to predict detachment pressures for mussel release testing. Equation 4 is valid for a distance range of 2.25 – 5.15 inches and velocity range of 215 – 570 ft/s. Similar to the spot jet data, nozzle distances less than 2.25 inches produced trends that varied from Figure 10 results. Additional fan jet data were collected using the 10 HP pump to provide accurate results for mussel removal tests where nozzle distance was less than 2.25 inches (Appendix B). Again, occasional pressures greater than 300 psi were detected.

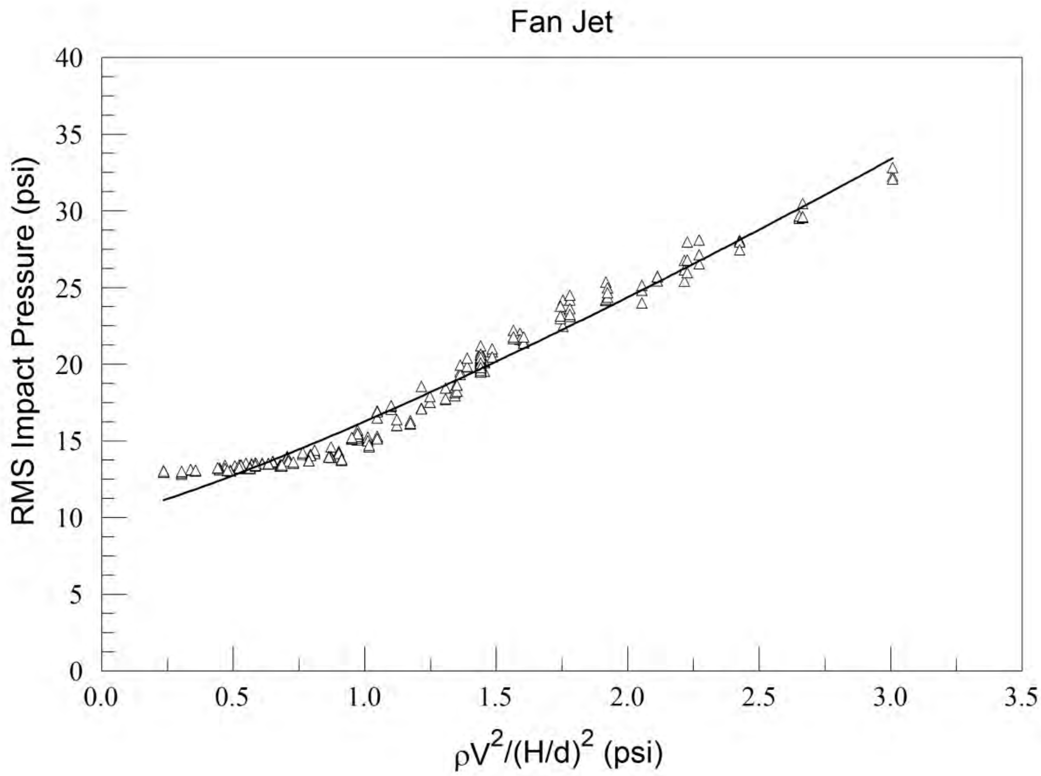

Figure 10 Impact pressure results for a 40 degree fan jet set at 45 degrees to the surface for release pressure testing. For this data set $R^2 = 0.972$.

$$P_{fanjet} = C_1 \left[\frac{\rho V^2}{\left(\frac{H}{d}\right)^2} \right]^n + C_2 \qquad (4)$$

Where: $C_1 = 6.226$

$C_2 = 10.057$

$n = 1.202$

ρ = density (slugs/ft^3)

V = velocity (ft/s)

H = nozzle distance from surface (inch)

d = nozzle diameter (inch)

Damage Pressure Testing

12 different coatings as well as galvanized steel were subjected to the durability test procedure. Table 5 shows the test parameters and pressure on the coating when damage was first identified. Coatings that were not damaged by the impinging jet were exposed to the jet for additional time (60 minutes) to see if time was a variable for the durability of that specific coating. Some coatings showed slight cavitation damage after 60 minutes while others could not be damaged at all by the jetting system. Prolonged cavitation exposure or mechanical damage would be required to test the durability of these coatings.

Table 5 Coating durability results from laboratory testing.

Type	Coating	Test #	H	Velocity	Time	Damage Pressure	Notes
-	-	-	*inch*	*ft/s*	*min*	*psi*	-
Conventional	DuraPlate 235	1	1/8	275	60	30.0	No visible damage
		2	1/8	275	60	30.0	
	Coal Tar Enamel	1	2 1/4	275	3	17.7	Dent in coating (1&3), hole formed and chunk removed (2)
		2	1 1/2	266	3	21.1	
		3	1 1/2	264	3	21.0	
	Tar Guard	1	1/8	275	60	30.0	Slight scarring and pitting near outside of jet
		2	1/8	266	60	30.0	
	Amercoat 240	1	3/4	267	60	29.2	No visible damage
Foul Release	HPL-2510 FR	1	1/2	275	60	30.0	No visible damage
		2	1/8	266	60	30.0	
	SeaSpeed V5	1	1/8	272	60	30.0	No visible damage
	Trunano	1	3/4	267	60	29.2	No visible damage
	Intersleek 970	1	2	269	3	18.5	Small hole in coating
	Rylar Experimental FR coating	1	3/4	267	60	29.2	No visible damage
	Fuji (White)	1	2	266	3	18.4	Small hole with visible cavitation pitting
		2	2	263	3	18.3	
	Fuji (Black)	1	2	279	3	18.8	Small hole in coating
		2	1 1/2	266	3	21.1	
		3	1 ½	266	3	21.1	Coating chunk peeled off
Exp.	1420 PFA	1	2	266	3	18.4	1/4" hole, chunk removed
		2	2	264	3	18.4	
	R3	1	1	266	3	25.5	1/2" chunk of coating peeled off
		2	1	264	3	25.4	
	Galvanized Steel	1	3/4	267	60	33.9	Discolored but no damage

Coal Tar Enamel was the only conventional coating that revealed damage during the 3 minute test. A small dent formed near the center of the jet but the coating was not torn or detached from the plate. This may be due to the plastic properties of the coating that allows it to deform without breaking down. Figure 11 shows the same sample after the 60 minute test. The dent was enlarged and significant pitting from cavitation impacts formed on the outside. While not unexpected, the high durability of conventional coatings is encouraging because these coatings are commonly used on much of Reclamation's hydraulic equipment and structures.

Figure 11 Photo of Coal Tar Enamel sample after durability testing. The center of the jet caused a small hole to form surrounded by cavitation pitting.

For the foul release coatings, those that are silicone based seemed to be the least resistant to jetting damage. The pressure of the impinging jet along with intense pressure fluctuations from cavitation caused the coatings to be either worn away forming a small hole in the coating layer or completely torn off of the plate in large chunks. Another observation was that durability was much more dependent on jet distance than jet velocity or even time of exposure. Figure 12 – Figure 14 show examples of damage from silicone based and experimental coatings for 3 and 60 minute tests.

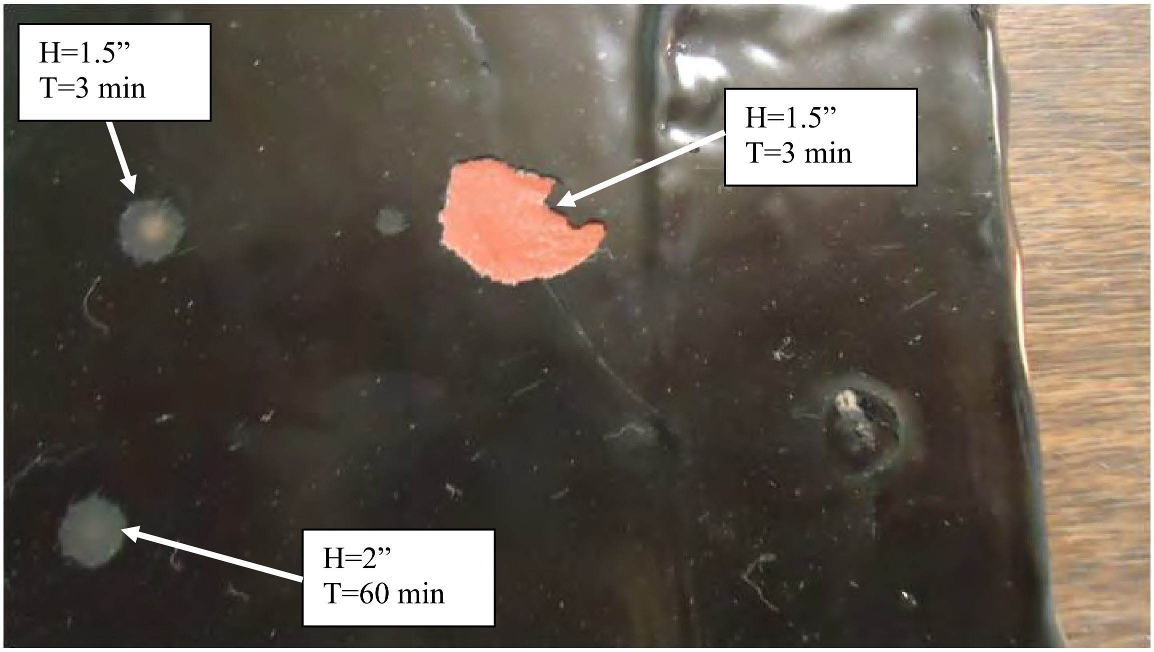

Figure 12 Fuji test sample; visible damage from 3 minute and 60 minute tests.

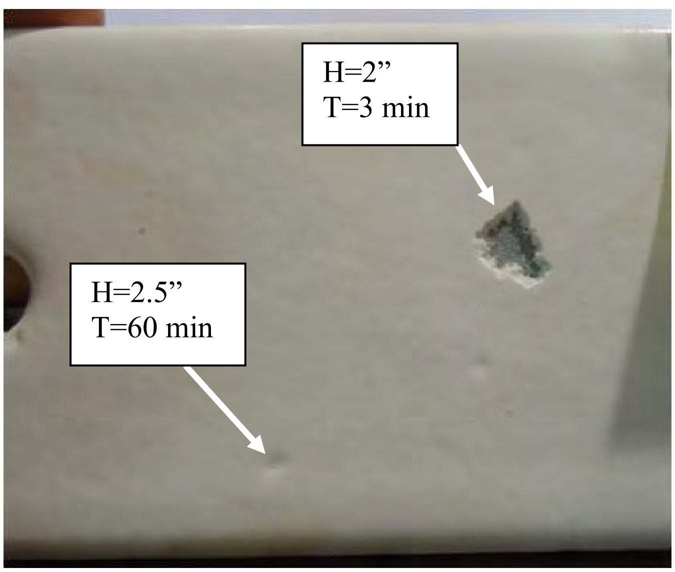

Figure 13 1420 PFA test sample; chunk removed from 3 minute test and slight dent (no damage) from 60 minute test.

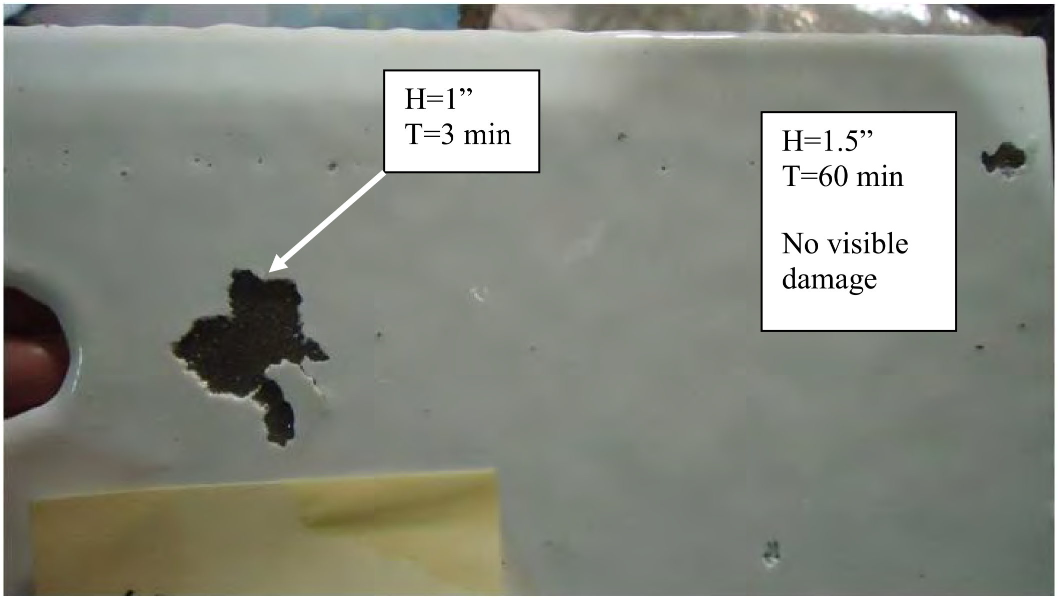

Figure 14 R3 sample; visible damage of coating peeled of test plate after 3 minute test. No damage was observed from 60 minute test with distance of 1.5 inches.

Release Pressure Testing

Mussel release testing showed very little difference in results among the various coatings (Table 6). The average pressure to remove attached mussels among all the tests was 13.6 psi. With the exception of peaks with the HPL-2510 and Amercoat systems the standard deviation is about 0.98 psi and the greatest difference among test results was 4.0 psi. The cause of higher pressures of these tests is unknown. Both of these coatings were tested twice and the high pressure peaks only occurred in December tests when water temperature was about 30 degrees cooler than tests in July.

Visual observation of the test plates before and after cleaning showed that the mussels did not release (let go or slide off) as expected but were rather torn off by the shear forces of the jet. This was indicated by the severed byssal threads and entrails of the mussels that remained attached to the plate (Figure 15). This seemed to be the only mechanism of failure as results and observations were similar for every coated and non-coated surface. The difference in pressure results may be the variation of byssal thread strength or failure mode as seen by Ackerman et al (1995), the significant difference in water temperature during testing or of the test measurement itself.

In MERL’s field experiments using shear push-off testing, foul release coatings have consistently outperformed conventional coating systems (Reclamation, 2012). It is believed that the reason for the difference between push testing and water jetting is that mussels are free to rotate in the jet flow and tend to orient themselves in such a way as to minimize hydrodynamic drag forces similar to observations made by Ackerman et al (1995). Consequently, the byssal threads or stem connections become severed by the intense lift force fluctuations and cavitation implosions of the jet before drag forces cause mussel removal from the surface.

Table 6 Mussel release results from field testing.

Type	Coating	Test #	Velocity	H	RMS Impact Pressure at Release
	-	-	*ft/s*	*inch*	*psi*
Conventional	DuroPlate 235	1	238	1.06	12.8
		2	233	2.47	12.3
		3	227	2.47	12.2
	Coal Tar Enamel	1	228	2.30	12.6
	Tar Guard	1	247	2.30	13.1
	Amercoat 240	1	288	1.37	19.7
		2	276	2.65	12.9
Foul Release	HPL-2510 FR	1	289	1.41	19.1
		2	244	2.30	13.0
	SeaSpeed V5	1	255	2.65	12.4
		2	272	2.65	12.8
	Trunano	1	227	3.00	11.4
		2	276	2.65	12.9
	Intersleek 970	1	228	2.83	11.6
	Rylar Experimental FR coating	1	267	2.65	12.7
Uncoated	Stainless	1	262	1.77	15.4
		2	228	1.77	13.6
		3	250	1.77	14.7
	Galvanized	1	250	1.94	13.6
		2	227	2.47	12.2

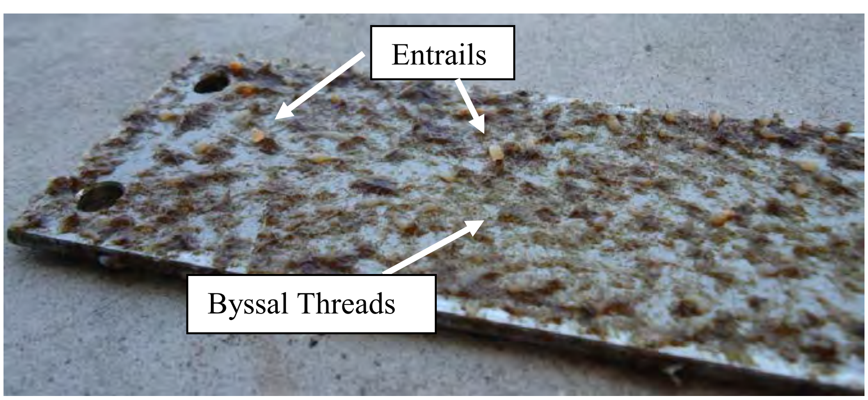

Figure 15 Byssal threads and entrails of mussels that were removed from a stainless steel plate during water jetting.

There was a large variation in the amount of mussels that were attached to the sample plates. In general there were more mussels attached to bare metal samples or conventional coatings than the foul release coatings. Often mussels would attach in clumps and would be 2 or 3 mussels thick. While the pressure required to remove mussels did not seem to vary with the amount of attached mussels, plates with less mussels were cleaner after jetting. Figure 16 and Figure 17 show a test sample before and after jet testing with mussels removed but byssal threads remaining after cleaning.

Byssal threads remained stuck to the surface of every test sample. Plates with significant mussel attachment were left with byssal threads and sometimes entrails that could not be removed with the jet. Even tests with the spot jet close to the surface were unsuccessful at completely removing the byssal thread remains (Figure 18). While it is undesirable to have threads remaining on the coating surface it may not be necessary to have them completely removed as they do not protrude into the flow enough to significantly increase flow friction or head differential.

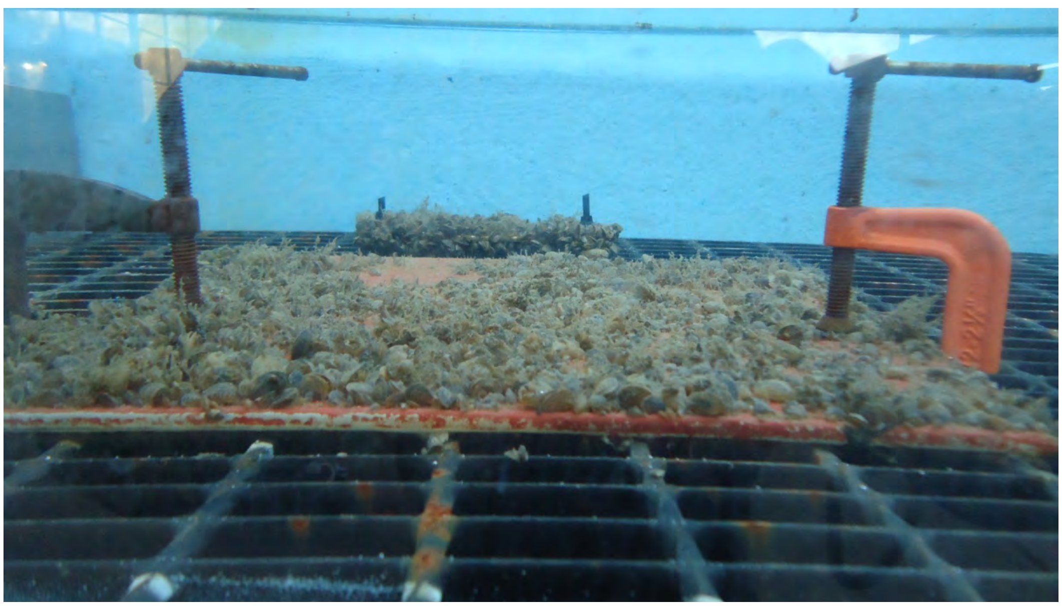

Figure 16 Seaspeed sample with live quagga mussels attached prior to testing for release pressures.

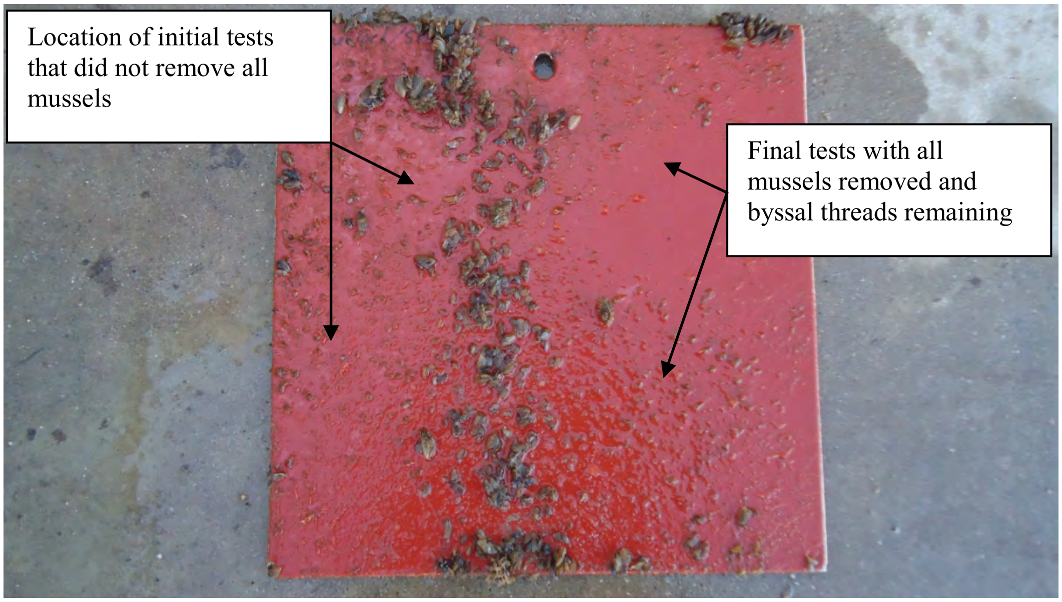

Figure 17 Seaspeed sample after release pressure testing. Mussels are removed where the proper jet distance and velocity were found (right side) but byssal threads remain on the plate.

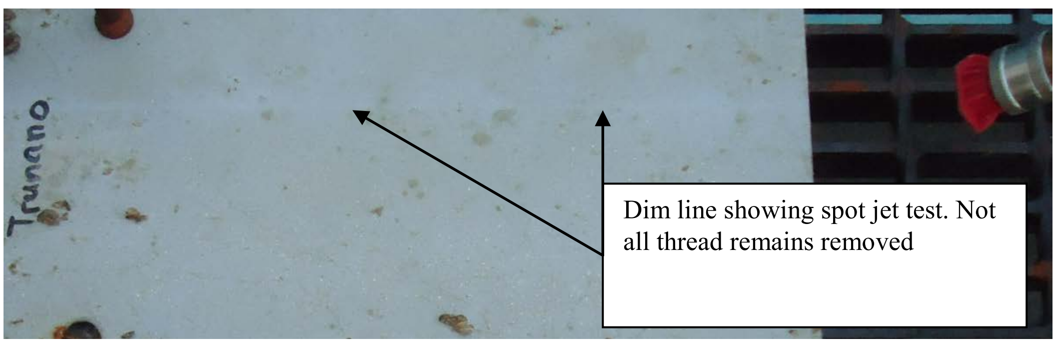

Figure 18 Attempt to remove byssal thread remains using a spot jet ½ inch from surface.

Figure 19, which summarizes average damage and release test results, shows a gap between the damage and release impact pressures for the coatings tested. This gap allows a range of pressures in which jetting operation would effectively remove mussels without causing damage to the coated surface. The minimum range is between 16.3 and 18.4 psi (mostly foul release coatings) and could be significantly extended depending on the coating system applied to the surface.

With information compiled in Figure 19, impact pressure equations can now be used to determine basic design parameters such as nozzle distance, orifice diameter and jet velocity for a controlled water jetting system. These basic design parameters can be used to design and size other system components such as the pumping and deployment systems. While additional impact pressure testing may be necessary for jetting systems with an extended range of hydraulic parameters, the operational limits defined for the coatings shown in Figure 19 should help provide guidance needed for future development and design.

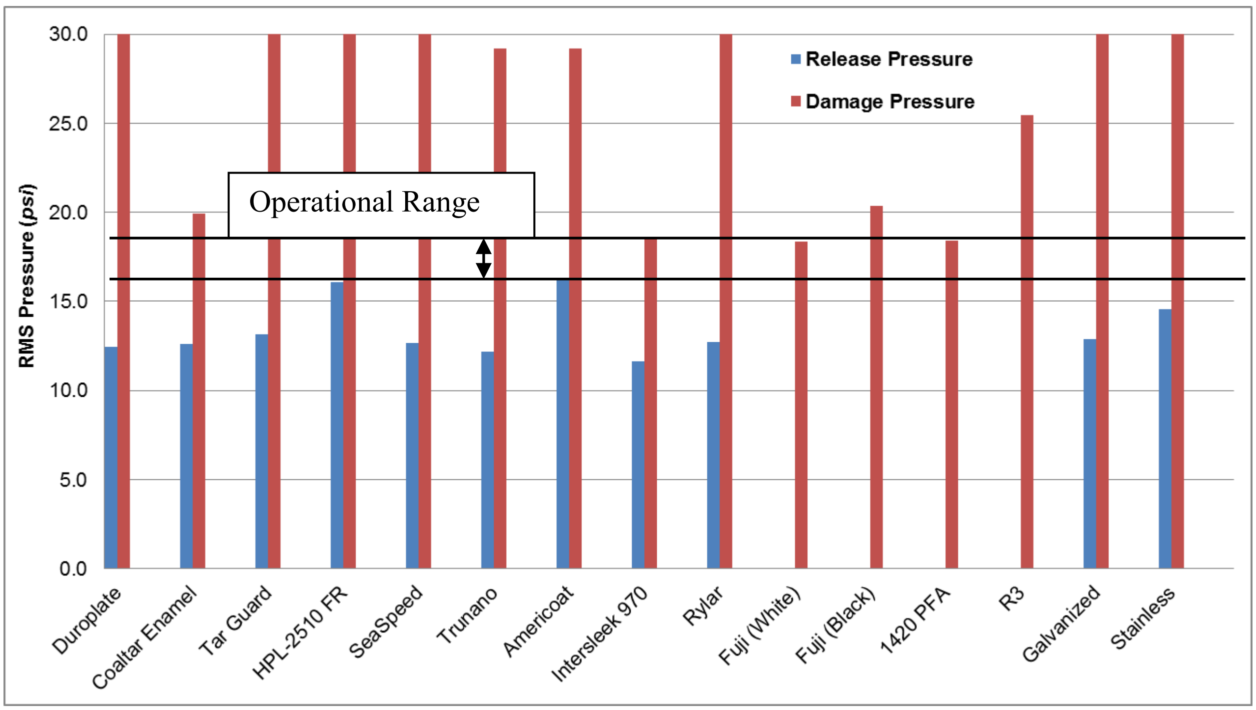

Figure 19 Average RMS impact pressure results for both mussel removal and coating damage.

Conclusions and Recommendations

A test procedure was developed to determine the required pressures from a submerged impinging jet to remove attached quagga mussels without damaging the surface coating or material. Fifteen different coatings or materials were subjected to the test procedure to define the water jetting limits for each specific coating. Test results showed that the jetting impact pressure required to remove mussels was independent of the coating or material type. This was due to the byssal threads of the mussel being torn apart causing the mussels to be forcibly detached from the surface rather than releasing. Byssal threads remained attached to the surface for all tests and could not be completely removed with the jetting system used in the current study.

Damage testing showed a wide range in durability among the coatings. In general the conventional coatings that are commonly found on existing Reclamation structures were more durable and resistant to the forces of the impinging jet. The foul release coatings that were silicone based were not durable and were more susceptible to damage. Despite the lack of durability of some of the coatings, in every case the damage impact pressures were higher than the pressures required to remove attached mussels. This gap in pressures allows a range of effective operation without exceeding the jetting durability limits of each specific coating or material. Within this range measureable hydraulic parameters can be used to design and size a water jetting system that is effective and compatible with multiple coatings.

It should be noted that impact pressures from hydraulic parameters outside of the range of this study are unknown and may be outside the appropriate operational range of the coating. If such hydraulic parameters are necessary for design, additional impact pressure testing should be conducted to verify that they can be used within the effective operating range.

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APPENDIX A

LITERATURE REVIEW

Table 7. List and description of literature that was reviewed related to protective coatings testing and water jetting for mussel removal.

No.	Title	Reference	Notes/Description
Water Jetting for Mussel Removal			
1	Quagga mussel control for pipes using water jetting	(Reclamation, 2010)	Describes a field test using a rotating water jet to remove mussels along the inside of an intake pipe. Pump pressures of up to 10,000 psi were used in the submerged pipe. The system was successful at removing the majority of mussel fouling. However, a few areas of biofouling remained along with areas where coating material was removed. No information was provided for pump pressures less than 10,000 psi.
2	High-Pressure Water Jetting and Carbon Dioxide Pellet Blasting	(US Army Corps of Engineers)	Technical note describing water jetting that has been used to remove zebra mussels from concrete surfaces. It is not mentioned whether jetting was submerged or unsubmerged. They recommend using pump pressures between 4,000 and 10,000 psi to remove mussels from concrete. The distance from the nozzle tip to the surface is an important parameter for this method.
3	Monitoring and Control of Macrofouling Mollusks in Fresh Water Systems	(Mackie & Claudi, 2010)	Discusses high and low pressure water cleaning used to remove mussels from unsubmerged concrete surfaces. Pump pressures of 3,000 psi were sufficient to remove a thick layer of mussels. They recommend also removing the byssal thread that is left from the mussels. Byssal threads that have not been removed may cause increased surface roughness for passing flows and may increase corrosion of the surface material. Operating criteria for removing all mussels and byssal threads without damaging the surface material were not mentioned.

No.	Title	Reference	Notes/Description
4	A wall jet to measure the attachment strength of zebra mussels	(Ackerman, Cottrell, Ethier, Allen, & Spelt, 1995)	A study of adhesion strength of individual zebra mussels to various types of substrates. A submerged wall jet nearly parallel to the boundary was used to detach mussels from the surface using a fluid detachment parameter to quantify adhesion strength. Observations showed that the mussels would orient themselves with the flow and their bodies lifted off the surface hanging on by only their byssal threads. Detachment resulted from 1 of 3 different mechanisms (1) failure of byssal pads (2) failure of byssal threads or (3) failure of connection of byssal stem to the body. Results showed that adhesion strength was dependent on substrate type.
Test Procedures			
5	F.I.T. Test Methods	(Center for Corrosion and Biofouling Control, Florida Institute of Technology, 2011)	Various ASTM standards developed to assess physical condition of coatings that have been biofouled as well as adhesion strength of hard fouling organisms using shear force measurements. Also, a method is discussed that evaluates adhesion strength of biofilms to a surface using a water jet test. While this information is not directly applicable to submerged cavitating jets information from the jet test method was helpful in developing test procedures used in the current study.
6	Standard Test Material for Erosion of Solid Materials by Cavitating Liquid Jet	(G134-95, 2010)	This ASTM standard describes a test procedure that uses a submerged cavitating jet to quantify material durability which is very similar to testing performed in the current study. However, in the current study the goal of the testing was to find coating durability which would more likely be damaged by impact pressure of the impinging jet rather than prolonged cavitation on the surface.

No.	Title	Reference	Notes/Description
7	Apparatus, Test Procedures, and Analytical Methods to Measure Soil Erodibility In Situ	(Hanson & Cook, 2004)	Discusses the test procedure and analysis of predicting soil erodibility using a submerged jet method. While their testing focused on erosion rate instead of incipient damage like the current study, some of their analysis methods may be applicable. Discusses equations to estimate stress on a submerged surface which may be applicable to coating testing.
Hydrodynamics of Submerged Jets			
8	Diffusion of Submerged Jets	(Albertson, Dai, Jensen, & Rouse, 1948)	The zones of flow establishment are described. Velocity of the jet remains unchanged for a certain distance from the exit (core length) which is about 6 orifice diameters for a circular jet. Velocities begin to decrease at greater distances with diffusion with the ambient fluid.
9	Pressure and Stress Distributions Due to a Submerged Impinging Jet	(Hanson, Kerry, & Darrel, 1990)	Describes pressure and stress distributions of a submerged jet on a planar boundary. Compare equations from literature to relationships developed from physical lab tests. Provides relationships of peak impact pressure and maximum shear stress from jet, which may be useful in quantifying coating durability for the current testing.
Cavitation			
10	Cavitation in Chutes and Spillways	(Reclamation, 1990)	Discusses what cavitation is, how it is formed and implications it may have on hydraulic structures and equipment. No information is given on effects to coatings which is one of the reasons for the current study.
11	Considerations in the Comparison of Cavitating and Plain	(Summers)	The width of a cavitating jet is approximately 3 times that which would occur where cavitation is not present. A round jet is capable of carrying energy to a much greater distance than a fan jet or spray whose

No.	Title	Reference	Notes/Description
	Water Jets		effectiveness decays very rapidly. Also cavitation produced within a nozzle in the center of the jet was much more intense that when produced as a result of the nozzle flow hitting the flow stream (i.e. cavitation produced on the outer surface of the jet).

APPENDIX B

ADDITIONAL FAN JET IMPACT PRESSURE DATA FOR NOZZLE DISTANCES LESS THAN 2.25 INCHES

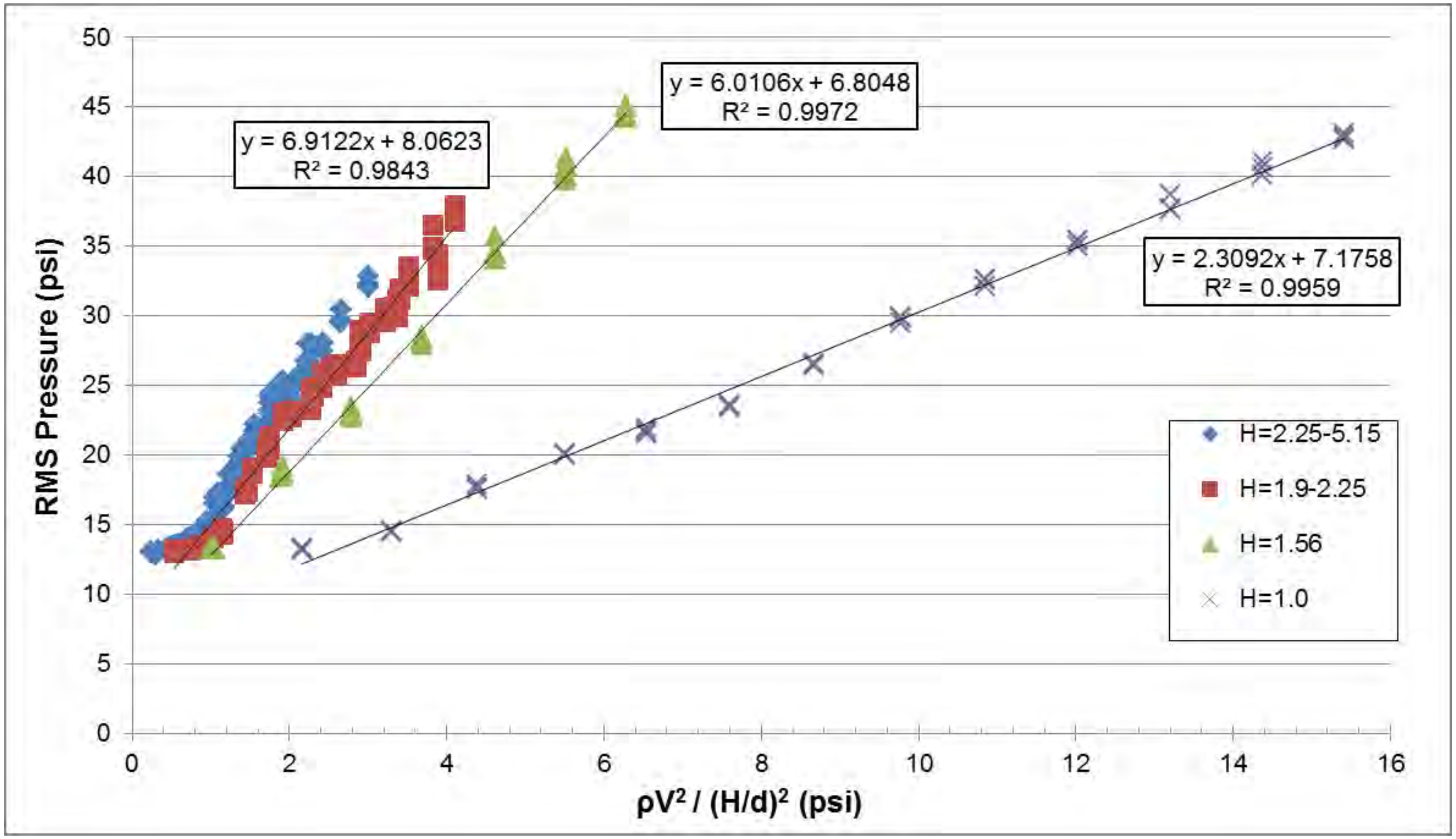

Figure 20 Fan Jet data sets for nozzle distances less than 2.25 inches. Equations on plot were used for pressure predictions for mussel removal data for close nozzle distances. Additional testing may be necessary for gaps in data (ex. H<1.0 inch or 1.0<H<1.56 inches).