RECLAMATION
Managing Water in the West

Final Report ST- 2015-7095-01

Coatings for Invasive Mussel Control – Final Report

Research and Development Office
Science and Technology Program

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

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Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

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.

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The Bureau of Reclamation Materials Engineering and Research Laboratory has evaluated more than 100 materials and coating systems for invasive mussel fouling control. Nineteen materials and coatings were found to prevent mussel attachment or are easily cleaned. Foul-release coatings do not contain biocides and are non-toxic. Instead, these coating rely on physical properties to prevent attachment. Laboratory test results show that other benefits of the foul-release coatings are improved resistance to water and ions and improved erosion resistance, compared to traditional epoxy coatings. This may increase the service life of the coatings provided the foul-release coatings remain intact and are not damaged mechanically. Foul-release coatings are not abrasion, impact, or gouge resistant and are easily damaged. They are UV stable and appropriate for immersion or alternating immersion and atmospheric service.

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Acronyms

°F	Degrees Fahrenheit
ADV	Acoustic Doppler Velocimeter
AS&M	Analytical Services and Materials
ASTM	American Society for Testing and Materials
AWWA	American Water Works Association
ECTFE	Polyethylchlorotrifluoroethylene
EIS	Electrochemical impedance spectroscopy
ETFE	Polyethyltetrafluoroethylene
FEP	Polyfluorinated ethylene propylene
FR	foul-release
ft	foot/feet
ft/s	feet per second
ft^3/s	cubic feet per second
HP	horse-power
Hz	hertz
in	inch or inches
lb(s)	pound(s)
MERL	Materials Engineering and Research Laboratory
MTA	Material Transfer Agreement
ONR	Office of Naval Research
PFA	Polyperfluoro alkoxy
PGA	Polyglycolic acid
PVC	Polyvinyl chloride
PVDF	Polyvinylidene fluoride
RPM	Revolutions per minute
RTV	Room Temperature Vulcanization
Reclamation	Bureau of Reclamation
SSPC	The Society for Protective Coatings
U.S.	United States
USACE	US Army Corps of Engineers
UV	ultraviolet

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EXECUTIVE SUMMARY

Invasive zebra and quagga mussels are a nuisance species that attach to most underwater surfaces. Their accumulation negatively affects the operation and maintenance of infrastructure, restricting water flow through intakes, trashracks, and small diameter pipe. The goal of this project was to identify coatings or materials that will prevent mussel attachment to the Bureau of Reclamation's (Reclamation) infrastructure.

Since 2008, Reclamation's Technical Service Center staff in the Materials Engineering Research Lab (MERL), in Denver, Colorado. Researchers have evaluated more than 100 coatings and materials for mussel control. The materials testing log is listed in the appendix at the end of this report.

This report details the results through the seventh and final year of testing. Earlier results are shown in a three (3) year report and a six (6) year report, available online [1 and 2].

Since the first year of testing, MERL has focused on finding foul-release coatings that prevent mussel attachment and have acceptable durability for use on Reclamation equipment. During the first year of evaluation MERL found that the anti-fouling paints, used in the marine industry, did not prevent mussel attachment in flowing water conditions. MERL has found a number of silicone-based foul-release (FR) coatings that prevent mussel attachment in both dynamic (flowing) and static (non-flowing) water conditions. Silicone FR coatings occasionally become fouled with aquatic vegetation and algae, which provide a surface for mussel attachment. The fouling can be cleaned from the surface with no measurable force. These coating systems do not contain biocides and strictly rely on surface properties to prevent mussel attachment. Unfortunately, silicone FR coatings are soft, and lack abrasion or gouge resistance. To date, MERL has not found a commercially available abrasion and gouge resistant FR coating that prevents mussel attachment. MERL recently evaluated Jotun Sealion Resilient, a hard FR coating, which allows weak mussel attachment, but self-cleans under the testing conditions. In addition, several experimental durable FR products from the Material Transfer Agreement (MTA) partner 2012-MTA-8-1003 have shown promise in preliminary tests, and have prevented mussel attachment for 30 months. Unfortunately, these formulations are not commercially available at this time. Table 1 shows the coatings and metal alloys that have performed well for controlling mussel attachment at Parker Dam, at Lake Havasu Reservoir on the lower Colorado River, between the States of Arizona and California, under site specific testing conditions. Other coating systems may work at different facilities under different environmental conditions.

Table 1.—Materials That Prevent Mussel Attachment or Are Self-Cleaning

Coating Type	Product Name	Results	Limitations	Test Period
Fluorinated silicone foul-release coating	International Paint Intersleek 970	A few mussels attach to the surface but are removed with very low force, self-cleaning properties	Soft Do not use in abrasion, gouge, or impact service environments	5/2008 to present
Silicone foul-release coating	Sherwin Williams Sher-Release	No mussel attachment, only algae and aquatic vegetation	Soft Do not use in abrasion, gouge, or impact service environments	5/2008 to present
	PPG Sigmaglide 890	No mussel attachment, only algae and aquatic vegetation	Soft Do not use in abrasion, gouge, or impact service environments	10/2009 to present
	CMP Bioclean SPG-H	No mussel attachment, only algae and plants. Small blisters formed on the coating after 3 years	Soft Do not use in abrasion, gouge, impact, UV, or splash zone service environments	10/2009 to present
	CMP Bioclean HB	No mussel attachment, only algae and aquatic vegetation	Soft Do not use in abrasion, gouge, impact, UV, or splash zone service environments	10/2009 to present
	Sherwin Williams Sher-Release Optimized Formulation	No mussel attachment, only algae and aquatic vegetation	Soft Do not use in abrasion, gouge, or impact service environments	3/2011 to present
	Nusil 9707	No mussel attachment, only algae and aquatic vegetation	Soft Do not use in abrasion, gouge, or impact service environments	5/2012 to present
	International Paint Intersleek 425	No mussel attachment, only algae and aquatic vegetation	Soft Do not use in abrasion, gouge, or impact service environments	12/2012 to present
	Hempel Hempasil X3	No mussel attachment, only algae and aquatic vegetation	Soft Do not use in abrasion, gouge, or impact service environments	12/2012 to present
	Jotun Sealion Repulse	No mussel attachment, only algae and aquatic vegetation	Soft Do not use in abrasion, gouge, or impact service environments	5/2013 to present
	Sherwin Williams Sher-Release (Oil Free)	No mussel attachment, only algae and aquatic vegetation	Soft Do not use in abrasion, gouge, or impact service environments	7/2012 to current
Silicone epoxy foul-release coating	Jotun Sealion Resilient	Mussels and algae do attach; however the release force is less than 0.2 lbs, self-cleaning	Hard Do not use metal on metal sliding surfaces	5/2013 to present

Coating Type	Product Name	Results	Limitations	Test Period
Not disclosed*	2012-MTA-8-1003 #1*	No mussel attachment	Unknown	12/2012 to present
Not disclosed*	2012-MTA-8-1003 #2*	No mussel attachment	Unknown	12/2012 to present
Automotive RTV silicone gasket	Permatex Red	No mussel attachment	Soft Do not use in abrasion, gouge, or impact service environments	5/2012 to present
	Permatex Clear	No mussel attachment	Soft Do not use in abrasion, gouge, or impact service environments	5/2012 to present
Copper metal antifouling coating	Copper Antifouling	Mussel fouling occurred in flowing water after 2 years. No mussels in static water. Blisters formed after 4 years	Leaches copper	5/2008 to 5/2014
Copper metal	Copper	Few mussels	Leaches copper	5/2008 to 5/2014
Bronze metal	Bronze	Few mussels	Leaches copper	5/2008 to 5/2014

A polyamide epoxy is a commonly used coating system for water immersion environments. The expected service life of an epoxy will depend on a variety of factors, but it is estimated to be about 15-20 years. Ideally, a successful FR coating would provide similar or better performance.

Laboratory tests further evaluated the FR coatings for corrosion protection and potential modes of failure due to mechanical damage. Silicone FR coatings provide a relatively strong barrier to water and ions to aid corrosion protection; their service life may exceed a three-coat epoxy system. FR coatings are also more ultraviolet (UV)resistant than epoxy coatings. The degree of corrosion undercutting in the accelerated tests (prohesion and modified prohesion) was unfavorable for a few FR coating systems, but this performance is directly related to the primer used. FR coatings are susceptible to mechanical damage due to poor abrasion, impact, and gouge resistance. Preliminary slurry erosion test results indicate that the FR coatings outperform epoxy coatings. This test simulates applications with heavy sediment loading in flowing water such as intake structures, piping, turbines, and pumps.

It is important for the coating specifier to know and thoroughly understand the environmental conditions of the infrastructure prior to selecting the correct products. Some products have additional limitations, for instance, Bioclean should not be used in water service environments with intermittent atmospheric exposure due to the poor UV stability and potential for delamination. Successful deployment of a silicone-based FR coating will depend strongly on the service environment. Environments where silicone-based FR coatings are in contact with brushing, abrasion, or gouging type cleaning equipment or debris impact should be avoided. Jotun Sealion Resilient appears to be more resistant to abrasion, gouging, and impact damage, but metal on metal sliding surfaces should be avoided. None of the coating systems are recommended for application over coal tar enamel.

INTRODUCTION

Zebra mussels were first discovered in the United States (U.S.) in the 1980s in the Great Lakes. Since then, both zebra and quagga mussels have spread rapidly across U.S. lake and river systems. In January 2007, quagga mussels were found in Lake Mead (the reservoir created by Hoover Dam). Mussels have spread downstream through the Colorado River aqueduct as well as the Central Arizona Project. Zebra and quagga mussels have been detected in many other reservoirs in the western U.S. Due to the warm climate of the southwest, mussel reproduction rates exceed those in the Great Lakes Region and Upper Mississippi River Basin.

Mussels have the potential to disrupt water delivery and hydropower generation functions and create long-term economic impacts. Mussels attach to underwater surfaces and can restrict water flow in small-diameter pipes (i.e., cooling water; ventilation, and air conditioning; and domestic water piping), restrict flow in larger diameter piping, clog fish screens, and impact intake structures.

Due to the potential impacts that mussels have at Bureau of Reclamation (Reclamation) facilities, a coatings research project was started in 2008 to identify coatings and materials that would prevent mussel attachment.

Most of the commercial products tested were designed for fouling control in the marine shipping industry. Service environments at Reclamation facilities present some unique challenges that must be considered when evaluating coatings for fouling control: highly variable water quality and abundant waterborne materials that affect durability, including sediment loads, woody debris, vegetation, ice, and other debris. While it is common to recoat ship hulls every 5 to 6 years, Reclamation infrastructure is less accessible, requiring a longer service life. Therefore, materials and coatings were evaluated to determine if they could meet Reclamation's needs. Prior to this study, Reclamation did not have a compelling need for coatings to address biofouling problems.

Prior Coating Research for Invasive Mussel Control

The U.S. Army Corps of Engineers (USACE) and Ontario Hydro were the first to encounter problems with mussels and conducted research on various materials to prevent mussel attachment. Both studies were conducted simultaneously in the 1990's. The results showed that some metal alloys, antifouling paints, zinc metallic coatings, and silicone foul-release coatings were effective at preventing mussel attachment [3, 4, and 5]. After reviewing the testing conditions at USACE and Ontario Hydro, Reclamation's Technical Service Center staff in the Materials Engineering Research Lab (MERL), in Denver, Colorado, observed that both studies were tested under quasi-static (low flow) conditions.

RECLAMATION'S FIELD TEST SITE

Parker Dam, at Lake Havasu Reservoir on the lower Colorado River, between the States of Arizona and California, (figure 1) was selected as the field test site to evaluate materials and coatings in quasi-static (low-flowing) and dynamic (flowing) exposure conditions. The mussels at this location reproduce almost year-round and have more reproductive cycles per year. For each coating system tested, three 1-foot-square steel plates were used in quasi-static exposure and were secured by a nylon rope and lowered approximately 50 feet (ft) into the water near the face of the dam. For the dynamic (flowing water) conditions, one 18-inch (in) by 24-in coated floor grate with 1-in spacing was tied off with two nylon ropes to prevent twisting and lowered to a depth of approximately 40 ft below the water surface. The samples were hung downstream from the forebay trashrack structure.

Figure 1.—Aerial photo of Parker Dam, CA. The red line indicates the location where the plates were placed, and the yellow line indicates where the grates were placed.

The coated plates were 12-in by 12-in by 3/16-in thick. The plates were prepared according to the Society for Protective Coatings (SSPC) SP1 solvent cleaning and abrasive blast cleaning to an SSPC SP10/NACE 2 near-white metal blast with three mil surface profile [6 and 7]. All coatings were applied in accordance with the coating manufacturer's recommendations, and in some cases, samples were shipped to the coating manufacturer for application. Figure 2 shows a set of coated plates being lowered into the water. The floor grate substrates were prepared and coated in the same manner as the plates. Figure 3 shows a coated floor grate prior to being lowered into the water.

Figure 2.—Coated steel plates placed in static exposure on the face of Parker Dam.

Figure 3.—Coated floor grate before being suspended from the forebay trashrack structure at Parker Dam.

ENVIRONMENTAL CONDITIONS

Velocity Measurements

In January and June, 2010, water velocity measurements were acquired along the trashrack structure and along the face of the dam where the static plates are located. Velocities near the static plates averaged 0.13 ft-per-second (ft/s).

Power plant flow rate measurements were 4,700, 9,800 and 15,000 cubic-feet-per-second (ft^3/s). Unfortunately, measurements were not collected when the plant was operating at maximum capacity (22,000 ft^3/s). The trashrack structure has 13 bays, with the bays numbered from south to north. In general, velocities varied with depth and across the trashrack structure with the lower velocities occurring at locations further from the penstocks. The velocity measurements were made with an acoustic doppler velocimeter (ADV).

The coated floor grates are approximately 40 ft below the water surface at elevation 410 ft. Figure 4 shows measured velocities during the lowest flow rate of 4,700 ft^3/s, figure 5 shows velocities at 9,800 ft^3/s, and figure 6 shows velocities at 15,000 ft^3/sec. The variability in measurement elevation was caused by strong currents moving the probe downstream and upward in the water column. At elevation 415 ft, the velocities varied from 0.3 ft/s to 0.6 ft/s when only one unit was operating. At 15,000 ft^3/s, the velocities were 1.5 ft/s to 2.0 ft/s. In general, velocities were largest on the south end of the trashrack structure (nearest the dam) and increased with depth. The velocity measurements at the dam face, where the static plates are located, were recorded at varying depths.

Water Temperature

Water temperature data were recorded on several test substrates from a period beginning October 20, 2009, through December 2012, at 15-minute intervals. Figure 7 shows temperature data at elevation 410 ft, 40 ft below the water surface. Quagga mussels are capable of reproducing at temperatures as low as 48^{o}F. Temperature data shows that at this facility the water temperatures would allow mussels to reproduce year round.

EXPERIMENTAL PROCEDURES

Following deployment, each coating system was evaluated at approximately six month intervals, around May and November of every year. The substrates were examined visually and photographed for image analysis. Mussel adhesion force data were recorded for use in a quantitative performance evaluation of each coating system. In addition, each stainless steel control substrate was

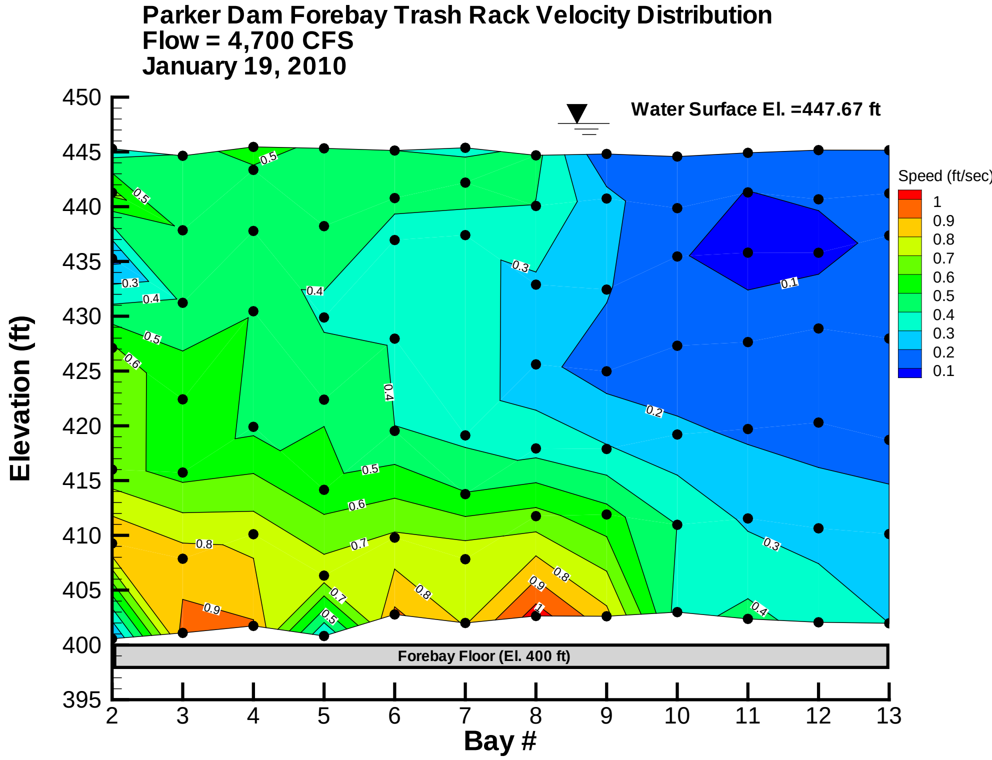

Figure 4.—Isovel plot of the velocity magnitudes passing through trashrack bays 2 to 13. The test grates were located near elevation 410 ft.

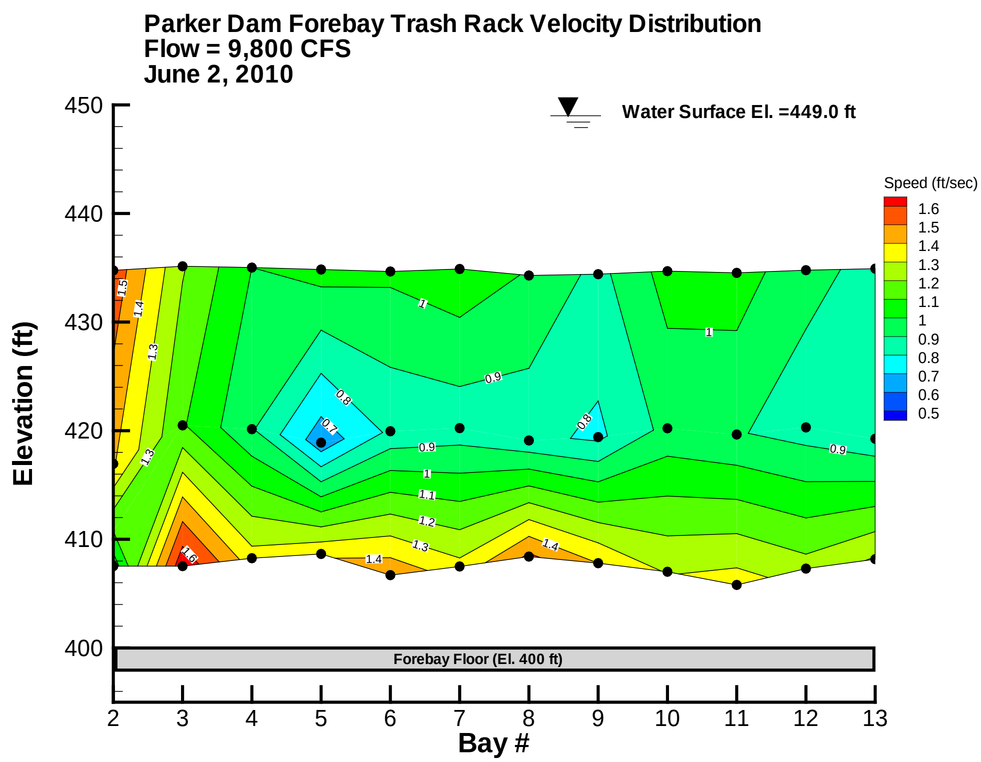

Figure 5—Isovel plot of the velocity magnitude passing through trashrack bays 2 to 13. Units 3 and 4 were discharging a cumulative 9,800 ft^3/s during the measurements.

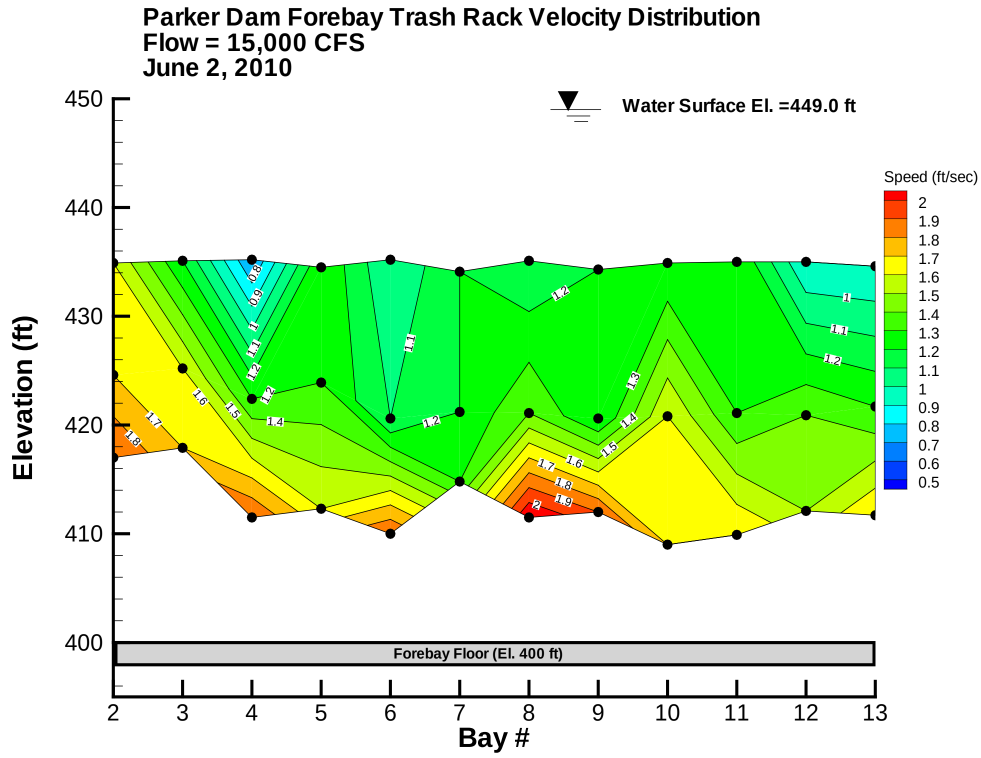

Figure 6.—Isovel plot of the velocity magnitude passing through trashrack bays 2 to 13. Units 1, 3, and 4 were discharging a cumulative 15,000 ft^3/s during the measurements.

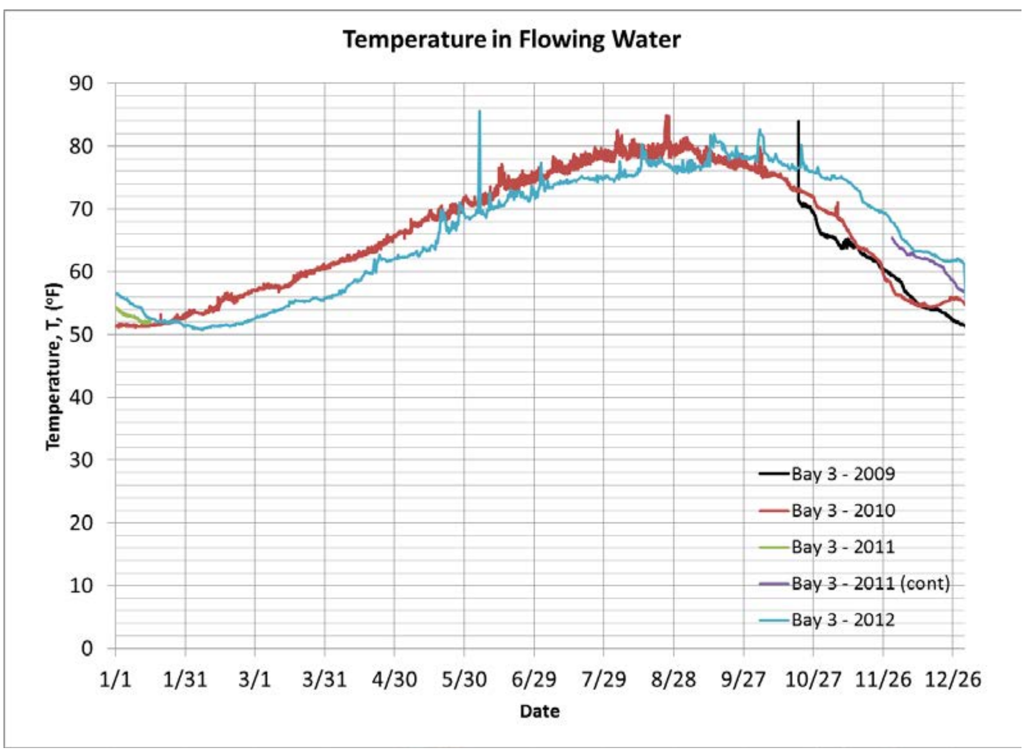

Figure 7.—Temperature data from 2009-2012 in bay 3 of trashrack structure, 40 ft below the water surface.

photographed and cleaned after every evaluation. Since mussel reproduction rates may vary from season to season and from year to year, control substrate monitoring helped to provide an estimate of the extent of fouling during the test duration. Greater populations of mussels on the control substrate were thought to correspond to increased competition for underwater surfaces, including the coated test panels.

Force Measurements

Mussel attachment strength was determined using a handheld force gage, namely Shimpo model FGV-5XY, with a maximum capacity of 5 pounds (lbs). The procedure was modeled after American Society for Testing and Materials (ASTM) D 5618-94, which is used to determine the attachment strength of barnacles [8]. The technique involves using a probe to apply a constant shear load to the mussel. The peak force recorded by the gage was taken as the attachment force. The primary deviation from the ASTM D 5618-94 procedure was that no attempt was made to measure the attachment area due to the difficulties of performing such a measurement with quagga mussels. It was impractical to identify the number of attached byssus threads in the field to estimate the corresponding surface area. Therefore, measurements were absolute forces and could not be quantified in terms of stress since the bond area was unknown.

Mussels can attach to the shells of other mussels and can grow into large masses. It was difficult to obtain any reproducibility in measuring force to remove a cluster of mussels. Also, the force to remove a cluster was much greater than to remove one mussel. To get a more reproducible result, single mussels between 3/8- and 5/8-in length were targeted to measure the removal force. It was decided to report the maximum force rather than an average force of several measurements due to the possibility that the weakly adhered mussels may only have a few byssal threads attached to the surface. In addition, the maximum attachment force gives a conservative measure of the bond strength that is possible for each coating over time.

Field Test Results and Discussion

Several sets of experimental controls were used to determine fouling rates and the presence of mussels, including epoxy-coated steel, ASTM A788 steel (figure 4) and 304 stainless steel [9 and 10]. Both steel and stainless steel fouled quickly; within a year mussels completely populated the grate, dramatically reducing the water flow through the 1-inch openings. A measured value of 1.7 lbs of force was needed to remove a single mussel. Figure 8 shows a steel grate after seven months exposure (May 2008 to December 2008) in dynamic conditions. Stainless steel controls were attached to every sample to observe the extent of mussel settlement for a given exposure cycle.

Figure 8.—Uncoated steel after 7 months of exposure in dynamic conditions. Test period May 2008 to December 2008.

Silicone and Fluorinated Silicone Foul-Release Coatings

Most silicone FR coatings and fluorinated silicone FR coatings evaluated effectively prevent mussel attachment. However, mussels can attach to accumulations of algae, biofilm, and aquatic plants on these surfaces, giving the false perception that they have attached to the coated surface. This is especially true for aquatic weeds wrapped on the leading edge or cross members. Quagga mussels do not attach to the silicone FR surfaces and in most cases require little or no force for removal, as seen in figure 9. The only exceptions were Analytic Service and Materials Inc. (AS&M) Aerokret 12xs and 21xs, which allowed mussels to attach to the surface. Most silicone and fluorinated silicone FR coatings showed self-cleaning once fouling had built up enough for drag forces to exceed the bond strength and peel the fouling material from the surface. During the summer months Parker Dam has higher flow rates and velocities due to an increased power demand (peaking power) and water demand for irrigation, this aides in the self-cleaning process. In general, there was significantly less fouling on the silicone and fluorinated silicone FR coatings during fall inspections than in the spring. Water velocities during the summer months ranged from 1.8 to 2.4 ft/s across the trashrack structure. During the winter months water velocities were 0.15 to 0.5 ft/s.

Figure 9.—International Paint Intersleek 970 easily cleaned, inspection date October 2009 after 18 months exposure.

In general, the silicone and fluorinated silicone FR coatings have been successful thus far in preventing or minimizing fouling. Limitations are foreseen for situations where debris is present in the water and that debris rubs, abrades, impacts, or gouges the coating. These coating systems should work well on infrastructure that is unaffected by such debris.

Silicone Foul-Release Theory

The silicone FR coatings are based on two key physical properties: low surface energy and low elastic modulus. Low surface energy prevents the mussel adhesive from wetting out the surface to form a strong bond to the silicone. The low modulus causes the fouling to release in a peeling mode rather than in shear, which requiring less force to remove fouling [11 to 15]. The literature suggests that silicone FR coatings function by interfering with the adhesion of marine fouling organisms, but hydrodynamic flow is required to remove fouling [16]. MERL experience has shown foul-release coatings prevent mussels from attaching in stationary and flowing water. This suggests that freshwater fouling organisms (i.e., zebra and quagga mussels) present a less complex problem to solve than their marine counterparts. Furthermore, by May 2015, several silicone foul-release coatings had been exhibiting mussel-free performance for durations in excess of seven years.

Commercially available silicone FR coatings contain silicone oils within the coating system that migrate to the surface over time, creating a surface that prevents adhesive wetting and bond formation. Systems are optimized to replenish oil on the surface for as long as possible, but eventually the oil becomes depleted. The performance typically degrades over time in a marine environment. MERL researchers questioned whether the silicone oil additive was essential for foul-release efficacy. Fuji Film (supplier for Sherwin Williams) agreed to provide an oil-free version for testing purposes, which was placed into testing in July 2012. To date this formulation does not allow mussel attachment to the surface (figure 10). This also suggests that as long as the silicone FR coatings are not damaged, they will perform for the life of the coating. MERL discovered that FR coatings prevent mussel settlement in freshwater compared to different fouling species attaching to FR coatings in marine environments. This revelation could lead to the formulation of FR coatings designed specifically for freshwater fouling control, which are better able to meet the needs of Reclamation and the industrial maintenance market.

Figure 10.—Fuji Film silicone oil-free after 34 months of exposure.

Durable Foul-Release Coatings

For purposes of this report, “durable” is defined as resistance to mechanical damage by brush cleaning equipment, gouging, impact, and abrasion. For instance, handling of a foul-release coated 2-ton structure using wide nylon straps would damage the silicone FR coating all the way to the epoxy primers. Damage that occurs prior to or during installation would lead to mussel fouling in those damaged areas.

All commercially available durable (hard) FR coatings that MERL tested allow mussels to attach to the coating surface with varying amounts of force, as shown in figure 11. The mussels build up significantly and can cause 100 percent blockage and severe flow restriction through the coated grates. Although the mussels attach with varying force, they remain attached to the surface without being released under the test conditions; i.e., the tested coatings are generally not self-cleaning. The only exception is Jotun Sealion Resilient, which allowed some mussel attachment. These mussels required 0.2 lbs of force for removal and sustained this self-cleaning performance for 24 months of exposure, and counting, as shown in figure 12.

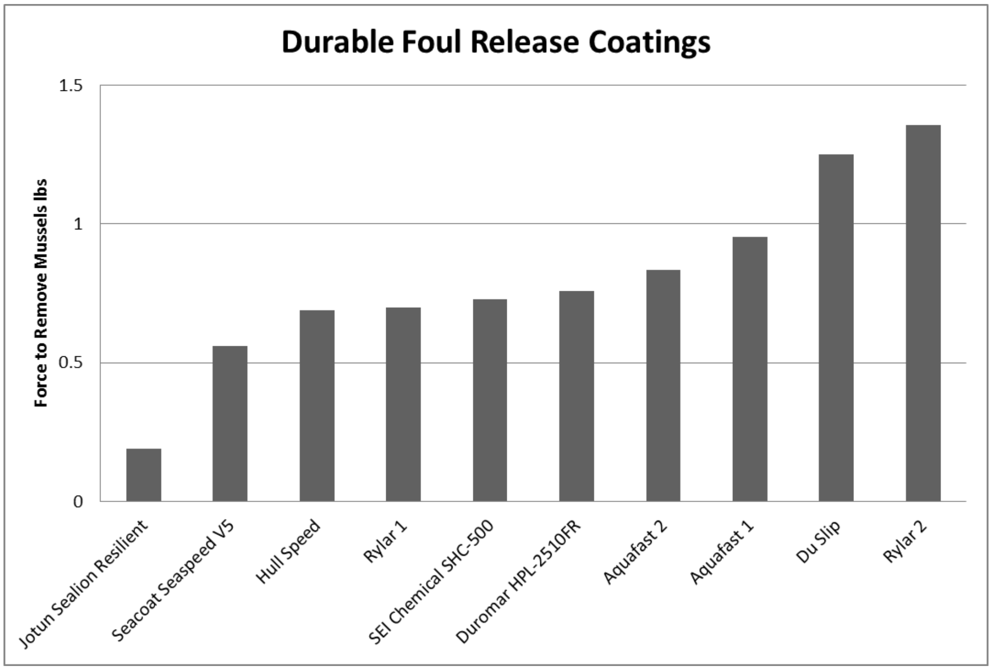

Figure 11.—Force measurements for durable FR coatings.

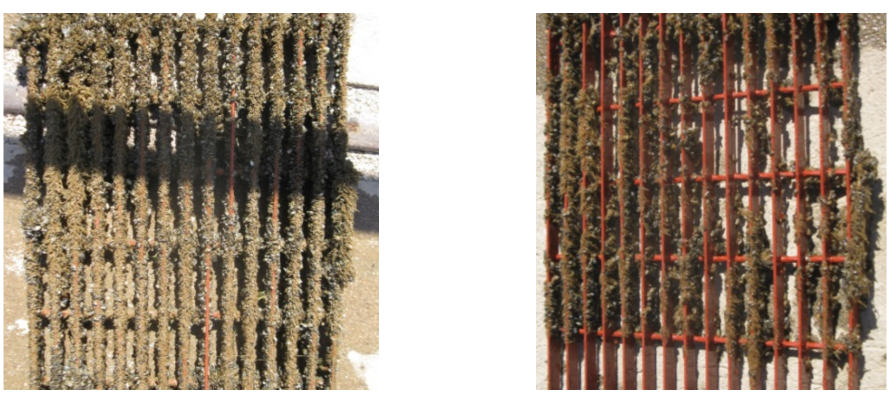

Figure 12.—Jotun Sealion Resilient, as seen in May 2015 (2 years of exposure) before cleaning (left) and, after cleaning by a forceful dip into the water (right).

EXPERIMENTAL SYSTEMS

Due to the performance of the commercially available hard FR coatings, MERL began investigating experimental products and set up Material Transfer Agreement's (MTA's) with six companies or universities. All MTA's prefer to have their identities private and not disclosed to the public. All MTA's were set up for field evaluation only, neither laboratory durability nor corrosion protection was evaluated. Most of the experimental formulations allow mussel attachment with varying degrees of force required to remove mussels. Figure 13 shows the removal force of the MTA experimental formulations.

Two experimental formulations under 2012-MTA-8-1003 prevented mussel attachment for 30 months of exposure, as shown in figure 14. Up to this point, prevention of attachment was only observed for silicone and fluorinated silicone FR systems. These formulations show that there is potential to have a durable coating and maintain equivalent performance of the silicone FR coatings.

In August 2014, partner 2012-MTA-8-1003 submitted two sets of reproducible panels and four new formulations. The reproducible panels provided equivalent performance to the panels previously tested. In addition, two of the four new formulations prevented mussel attachment. Now, partner 2012-MTA-8-1003 has four durable formulations that prevent mussel attachment.

Partner 2012-MTA-8-1004 provided four experimental formulations. Sample #1 had approximately 30 percent of the surface covered with mussels, but no measureable force was required to clean the mussels off the surface. Unfortunately, this formulation was severely blistered and was removed in May 2014. Samples #2, #3, and #4 did not show any resistance to mussel fouling, and more than 1.0 lb of force to was required remove the mussels from these samples.

Partner 2012-MTA-8-1005 provided five experimental formulations. All five samples showed heavy mussel fouling with moderate force required to remove the mussels. These five formulations had release forces between 0.4 to 1.3 lbs of force, which was equivalent to other durable FR coatings tested prior to December 2012.

Partners 2014-MTA-8-1008 provided one experimental formulation. This formulation was evaluated between May 2014 and December 2014. Mussels attached to the surface requiring 0.7 lbs of force to remove mussels.

Partner 2014-MTA-8-1009 provided four experimental formulations. These formulations were evaluated between May 2014 and December 2014. Mussels attached to all the formulations, varying from 0.3 to 0.6 lbs of force to remove mussels.

Partner 2014-MTA-8-1010 provided 10 formulations. These samples went into testing December 2014, and there is not sufficient data at this time. All of these formulations are silicone based coatings at varying degrees of reinforcement.

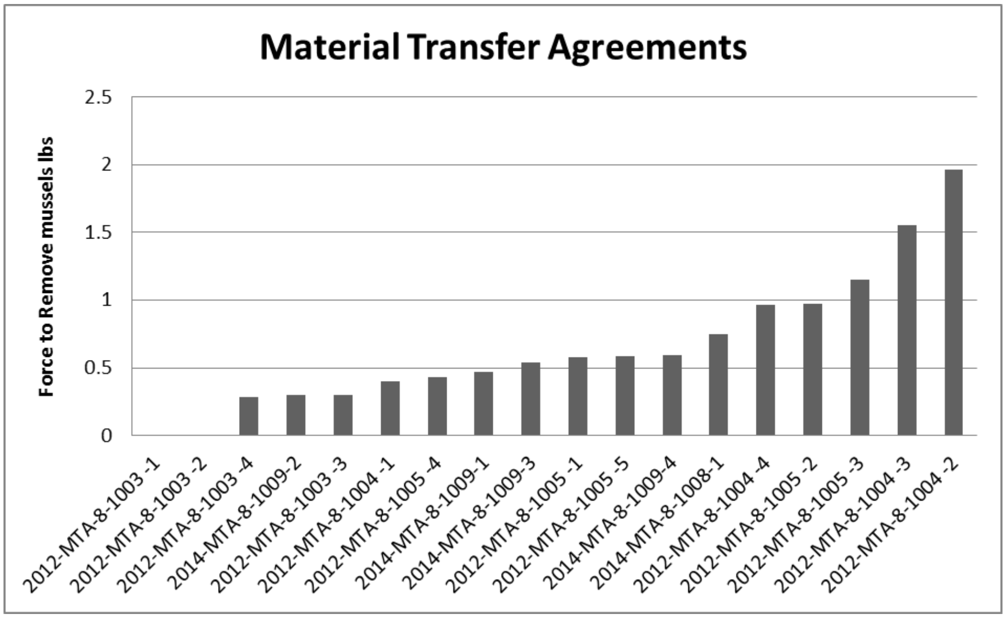

Figure 13.—Force to remove mussels from coated panels received through Material Transfer Agreements.

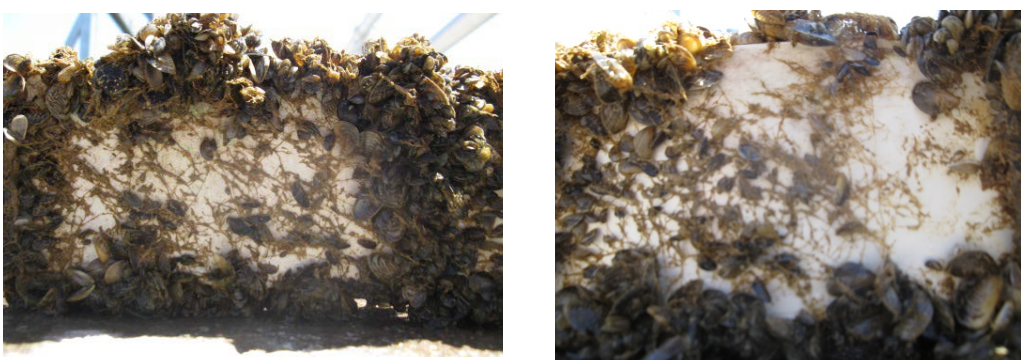

Figure 14.—Panels coated with experimental formulations from 2012-MTA-8-1003 #1 (left) and #2 (right), exposure at 30 months.

Low Coefficient-of-Friction Coatings

Low coefficient-of-friction coatings were not designed to prevent mussel attachment; however, MERL found that some of them have lower release force than most of the hard FR coatings. Figure 15 shows the release force for mussels of various low coefficient-of-friction coatings. Even though these coatings have low release forces, the coatings allow mussels to attach and are not self-cleaning under the testing conditions at Parker Dam. It is unknown if these coatings would self-clean under higher flow rates.

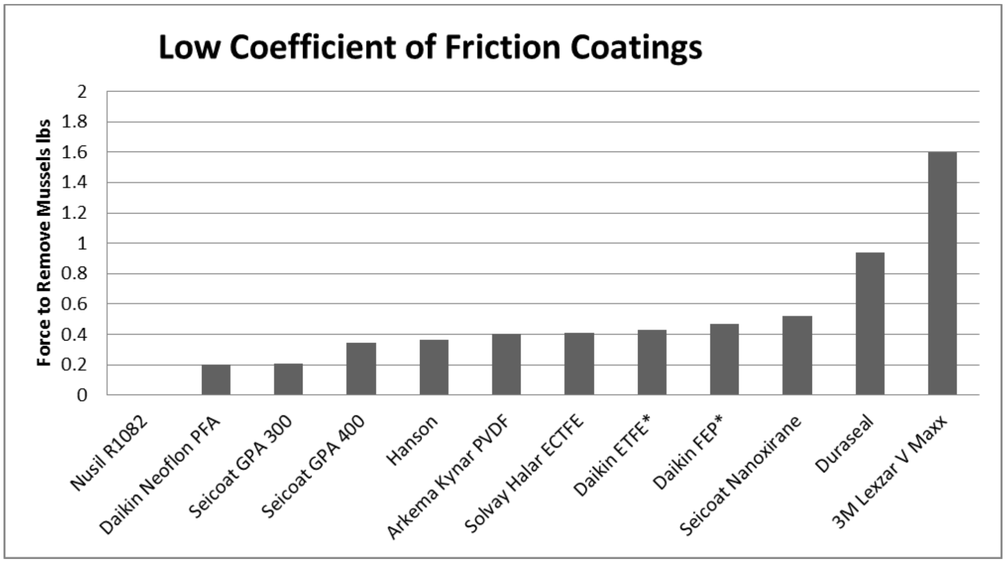

Figure 15.—Force measurements for low coefficient-of-friction coatings.

Fluorinated Powder Coatings

MERL evaluated five fluorinated powder coatings. These coatings were not designed as FR coatings but rather as “non-stick” coatings. The coatings evaluated were Arkema Kynar PVDF, Solvay Halar ECTFE, Daikin ETFE, Daikin FEP, and Daikin PFA. Mussels attached to all of these coating systems. Approximately 0.4 lbs of force was required to remove a mussel from the PVDF, ECTFE, ETFE, and FEP. Only 0.20 lbs was required to remove a mussel from the PFA, which was the best performing of the fluorinated powder coatings. These coatings are moderately durable and could offer moderate resistance to abrasion, impact, and gouging damage.

Anti-Ice Coatings

MERL evaluated three products that were designed to prevent ice from adhering to surfaces. 3M Lexzar V Maxx and Hanson (evaluated from November 2011 to December 2012) had mussel attachment and required 1.6 lbs, and 0.3 lbs, respectively, for removal. 3M Lexzar V Maxx allowed 90 percent blockage, and Hanson allowed 100 percent blockage in one (1) year. Nusil R1082 allowed mussels to attach to the surface, but require extremely low force for removal. The force was non-detectable for a single mussel and less than 0.40 lbs for a cluster of mussels. Nusil R1082 has the potential to self-clean under higher flow rates. When mussels were removed, the entire byssal thread was also removed from the surface, seen in figure 16. Nusil R1082 is a reinforced silicone, making it stronger than silicone FR coatings. Nusil R1082 is not self-cleaning under the testing conditions, but might be useful for infrastructure that has cleaning equipment, such as fish screens, or on infrastructure or boat bottoms that have higher flow rates. Nusil R1082 has provided some important insight for understanding the mussel attachment mechanism.

Figure 16.—Grate treated with Nusil R1082 silicone ice phobic coating, before cleaning (left) and after cleaning (right), 12 months.

Silicone Anti-Graffiti Coating

Seicoat GPA-300, GPA-400, and Nanoxirane are silicone-based coating systems designed for anti-graffiti resistance . These systems are primarily used in an atmospheric environment. GPA-300 has approximately the same durability as the silicone FR coatings, whereas GPA-400 and Nanoxirane are significantly more durable. Mussels attached to the coated grate, blocking 85 percent of the flow. The force to remove the fouling was very low for GPA-300 (0.2 lbs) but moderate for GPA-400 (0.3 lbs) and Nanoxirane (0.5 lbs). The products were removed from testing after 1 year.

Molybdenum-Disulfide Containing Coating

Molybdenum sulfide is used as dry lubricants and additives in hydraulic oil for lubrication. There was no data on the usefulness as deterrent for mussel attachment. MERL evaluated Duraseal, a coating which contained molybdenum-disulfide. The product has a low coefficient of friction and excellent abrasion resistance. The product was evaluated from November 2011 to December 2012, and became 100 percent blocked, and 0.9 lbs of force was required to remove mussels.

Antifouling Paints

Antifouling paints contain biocides to prevent fouling. All of the antifouling paints evaluated had a limited service life of one (1) to two (2) years in flowing water. Their longevity improved in quasi-static exposure. All of the antifouling coatings have been withdrawn due to the superior performance of non-toxic silicone FR coatings.

Luminore was evaluated beginning in 2008. The mussels did not attach in flowing water for one (1) year. After the second year, the grate was blocked about 29 percent with mussels and was withdrawn at the two (2) year inspection in 2010. It required 0.8 lbs of force to remove a single mussel. The coated substrates in quasi-static water were mussel-free up to six (6) years in exposure. The leach rate of the biocides depends upon many factors. In this case, it is clear that the velocity of the water causes the copper to leach at a higher rate.

Copper Alloys

Initially, copper, brass, and bronze all prevented the mussels from attaching. Occasionally, a large adult mussel attached to the metal surface of the brass or bronze plates. When a mussel attached to either of these surfaces, it adhered well. Removing a single mussel required 1.3 lbs of force. The brass began having heavy mussel attachment in May 2010 after two (2) years in immersion. The mussels did not adhere to copper nearly as well, requiring only 0.3 lbs of force for removal. Copper was more effective than brass or bronze and remained essentially free of mussels after six (6) years of testing. The original copper thickness was 0.125 in and, after six (6) years, it measured 0.11 in. That computes to 1.25 mils metal loss per year per side. When designing or using copper as an alternative mussel control strategy, one should estimate a metal loss in order to determine the usable service life. Actual metal loss will depend on several factors, including water chemistry, exposure, and environmental conditions. Another thing to be concerned about is the concentration of copper that is being released into the water. The 90/10 copper/nickel alloy allowed immediate mussel attachment and was withdrawn after four (4) months of exposure.

Zinc-Rich Primers

MERL evaluated two (2) inorganic and one (1) organic zinc rich primers. MERL observed that zinc-rich primers only allowed a few mussels to attach in the quasi-static environment. However, all zinc-rich primers evaluated had significant mussel colonization on the grates in flowing water, with 75 to 100 percent blockage after seven (7) months of exposure [17]. All samples failed to meet the criteria and were removed after seven (7) months.

Zinc Metallic Coatings

Galvanized steel, a 100 percent zinc thermal spray, and an 85/15 zinc/aluminum thermal spray prevented mussel attachment in the quasi-static environment [17]. However, under dynamic conditions high densities of quagga mussels attached to the metallic coated grates, causing 50 to 100 percent blockage after seven (7) months [17]. All samples were removed after seven (7) months of exposure.

Biodegradable Polymer

A biodegradable polymer sheet of polyglycolic acid (PGA) was evaluated in July 2012. This polymer is primarily used in the biomedical industry for dissolvable sutures, pins, and screws [18]. The thought was that the polymer would slowly hydrolyze and release the fouling as it eroded away. MERL found that PGA allowed a few mussels, aquatic plants, and algae to attach to the surface. The fouling was easily removed, requiring no measurable force, similar to the silicone foul-release coatings. There was only one (1) mussel that attached to the PGA surface, and it required 0.2 lbs of force to remove it; otherwise, all the mussels were attached to the aquatic plants.

PGA is a strong plastic that slowly hydrolyzes and would have a finite service life; however, since it is a plastic and is not suitable as a coating, it may have limited use for Reclamation. The material degradation rate would have to be tailored to obtain an acceptable service life, while still releasing the fouling species. This can be accomplished through blends of polyglycolic acid and polylactic acid. MERL determined that PGA degrades approximately 1 millimeter per year. In December 2013, the sample had decomposed and was lost.

Automotive Silicone Gasket Materials

In May 2013, MERL tested automotive room temperature vulcanization (RTV) silicone gasket materials used for oil pans and engine blocks. These gasket materials were more tear and abrasion resistant than the traditional silicone foul-release coatings. Automotive gaskets were selected because they did not contain mildewcide, in contrast with silicone caulking compounds from a hardware store. It was unknown if a mildewcide would affect the mussels; therefore, MERL chose to test materials that did not contain a mildewcide.

Six (6) different RTV silicone gasket materials were selected with varying mechanical and physical properties. Two (2) of the six (6) gasket materials prevented mussel attachment following 24 months of exposure: Permatex Red and Permatex Clear. The surfaces of the gaskets were very rough due to the high viscosity of the liquid applied gasket materials.

Laboratory Test Results and Discussion

Corrosion Protection

Protective coatings are the primary means of providing corrosion protection. Reclamation needs to maintain corrosion protection regardless of whether invasive mussels are fouling Reclamation's infrastructure. It is standard practice for MERL to test coatings for corrosion protection and resistance to weathering, using ASTM tests such as ASTM D 870 Water Immersion [19], ASTM D2794 Direct impact [20], ASTM D5894 Prohesion [21], and ASTM D4587 QUV [22]. The foul-release coatings were evaluated against coatings currently specified by Reclamation because the foul-release coatings require primers that were not currently approved as equivalent products. Table 2 shows the results of the accelerated weathering, direct impact, and abrasion resistance testing.

Table 2.—Laboratory Test Results

	Prohesion ASTM D5894 Undercutting	Modified Prohesion + immersion cycle Undercutting	QUV ASTM D4587	Direct impact ASTM D 2794	Abrasion Resistance
Polyamide epoxy (Specifications)	3/16"	1/4"	Chalked and yellowed	30 in-lbs	Yes
Jotun Sealion Resilient	21/32"	5/16"	Slight discoloration	32 in-lbs	Yes
Jotun Sealion Repulse	3/16"	7/32"	No change	2 in-lbs	No
International Paint Intersleek 425	1/4"	3/16"	No change	2 in-lbs	No
International Paint Intersleek 970	13/32"	1/4"	No change	2 in-lbs	No
Nusil 9707	1/4"	13/32"	No change	2 in-lbs	No
Sherwin Williams Sher-Release	3/8"	1/2"	No change	2 in-lbs	No
CMP Bioclean SPG-H	1/8"	7/16"	Delaminated	2 in-lbs	No
PPG Sigmaglide 890	13/32"	13/32"	No change	2 in-lbs	No
Hempel Hempasil X3	N/A	N/A	No change	2 in-lbs	No

The accelerated weathering test, ASTM D5894 prohesion, cycles between a salt fog and ultraviolet (UV) light weathering on a weekly basis. Three (3) panels were scribed and evaluated after 5,000 hours of exposure. The extent of under film corrosion creep (undercutting) was measured. Most of the specified coatings have a ¼-in undercutting or less after 5,000 hours of exposure. Since the FR coatings use corrosion resistant epoxy primers, the extent of undercutting is highly dependent on the epoxy primers. Most of the epoxy primers specified for the foul-release coatings provide good to excellent undercutting resistance. The exception was the primer used on Jotun Sealion Resilient. After consulting with the manufacturer, Jotun Jotamastic 90 could also be used for the resilient system, as it was used for the repulse system.

MERL developed a testing procedure modifying the prohesion test that incorporates a water immersion cycle to simulate alternating atmospheric and immersion service conditions. This is a common exposure condition on trashracks and intake structures that have significant mussel fouling problems. The modified prohesion test is more aggressive than the prohesion test that allows for further undercutting caused by water and ions migrating under the film. Reclamation has observed greater corrosion rates at the splash zones, such as Parker dam trashrack seen in figure 17. Most of the specified coatings have ¼ in undercutting or less after 5,000 hours of exposure. Only three (3) of the FR primers were less than ¼ in. Therefore, it is highly recommended to use approved primers prior to applying the foul-release coating system.

Figure 17.—Parker Dam Trashrack fluctuating water zone, prior to replacement.

Because Reclamation's intake structures have fluctuating conditions, atmospheric weathering was evaluated. QUV (weather testing of polymers) artificially simulates UV degradation. The standard epoxy coating chalk and yellow as a result of this exposure. Most silicone and fluorinated silicone FR coatings are UV stable. The exception to this rule was CMP Bioclean SPG-H, which delaminated under UV conditions. It's believed that Bioclean contained a clear topcoat and that the UV penetrated to the epoxy primers, cause degradation at the epoxy/silicone interface. It is not recommended to use Bioclean under alternating immersion/ UV conditions. The Jotun Sealion Resilient is an epoxy silicone hybrid and sustains some chalking during UV exposure. It is unknown whether or not this affects the coating's ability to prevent mussel fouling.

Direct impact, was used to determine the amount of impact force a coating can withstand before cracking, delaminating, or damaging. The epoxy controls typically withstand 30 in-lbs of force before damaging. The only system to withstand equivalent force was the Jotun Sealion Resilient. All other foul-release coatings have poor impact resistance.

Another test developed by MERL was a brush abrasion test to simulate cleaning equipment for fish screens. Abrasion testing was performed using a reciprocating Linear Taber Abraser test machine (model 5750) equipped with an extra course abrasive bristle brush purchased from Ace Hardware. A 3- by 6-in panel was submerged in 10 ounces of filtered water in an acrylic tub and held in place by two (2) C-clamps as shown in figure 18. Weights were placed on a splined shaft connected to the brush to control the normal force exerted on the coated surface. The brush was cycled back and forth 1,500 times at a speed of 75 cycles per second, creating a wear track on the coating. The test panel was then removed from the solution and allowed to dry overnight. Following drying, the coating was weighed to determine material loss due to abrasion. This process was repeated to achieve a total of 4,500 cycles. Three (3) wear tracks were created using three (3) different weight levels: 0, 500, and 1,000 gram weights were added to the splined shaft (4,500 cycles per track). The weight of the splined shaft assembly was approximately 380 grams. Only the Jotun Sealion Resilient and the control Sherwin Williams Duraplate 235 were able to withstand the abrasion.

Figure 18.—Brush abrasion test setup.

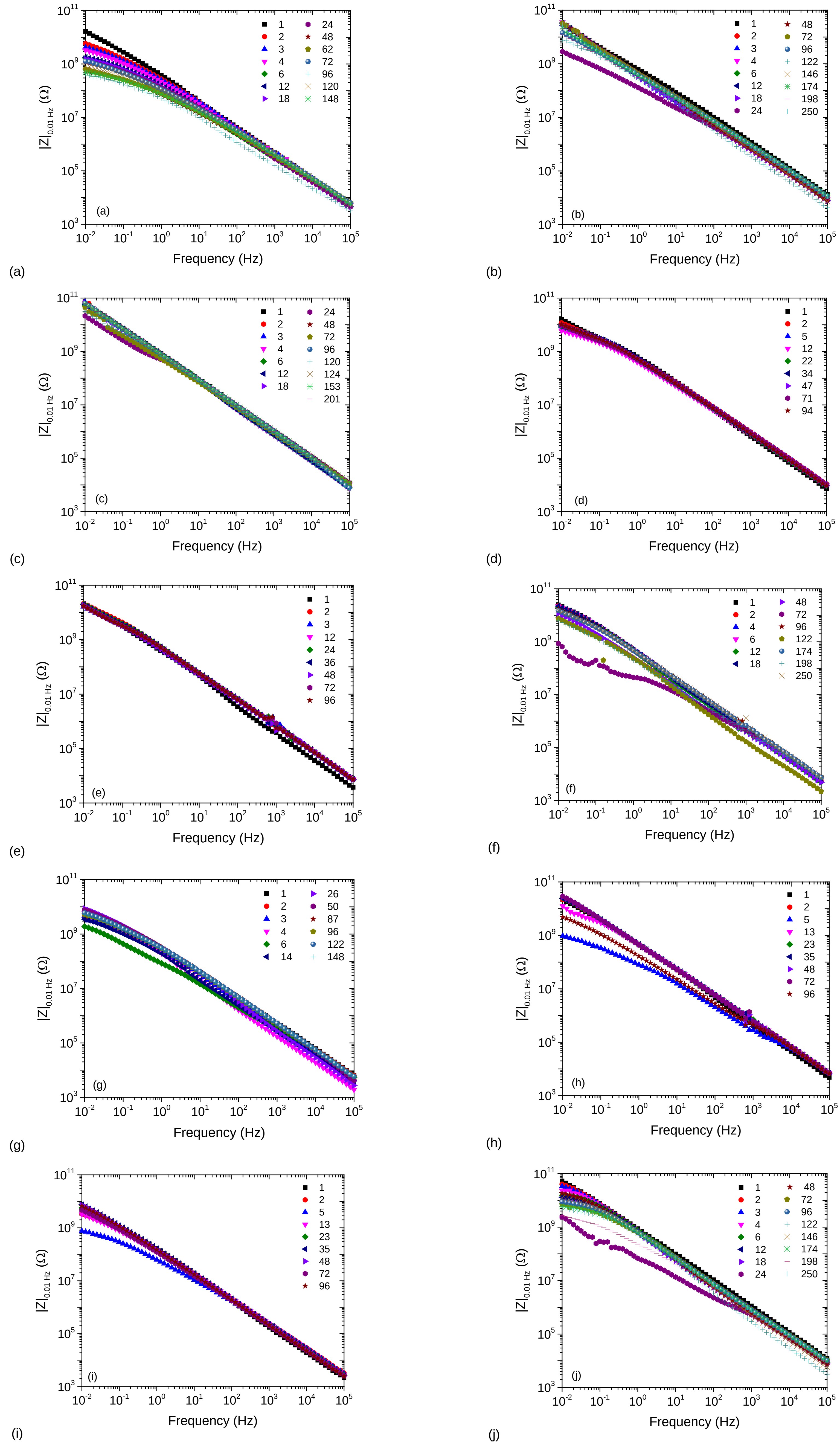

Figure 19.—Impedance magnitude plotted versus acquisition frequency for all measurement periods; cumulative exposure period shown as time in weeks for each trend line: (a) Duraplate 235—standard coating system for corrosion protection, (b) Bioclean SPG-H, (c) Sher-Release, (d) Hempasil X3, (e) Intersleek 425, (f), Intersleek 970, (g) Nusil 9707, (h) Sealion Repulse, (i) Sealion Resilient, (j) Sigmaglide 890.

Coatings were evaluated by water immersion ASTM D870 using deionized water and a dilute Harrison solution, containing 0.5 grams of sodium chloride and 3.5 grams ammonium sulfate per liter of water. The exposure period for the immersion test was a minimum of two (2)years. Electrochemical impedance spectroscopy (EIS) was used to evaluate the migration of ions and water through the coating as well as to monitor for corrosion under the coating. Figure 19 shows the EIS results for the FR coatings. In figure 19(a), the standard epoxy shows the impedance value drop at lower frequencies (less than 10^{-1} hertz [Hz]) over time. This indicates the coating is allowing more ions through the coating, thus reducing barrier properties as exposure progresses. Interestingly, most of the FR coatings show greater barrier properties and degrade much slower than the standard epoxy coating alone. This could be due to the hydrophobic nature of the FR coatings. Figure 20 shows the impedance values at 0.01 Hz versus exposure time as a characterization of each coating's total resistance to water ions, or the total impedance, which is an indication of the full barrier performance. The standard epoxy coating has a large drop in impedance within the first four (4) to six (6) weeks of exposure due to water absorption and experiences a steady degradation from 25 to 150 weeks. The foul-release coatings appear to be more stable showing superior barrier properties compared to the epoxy.

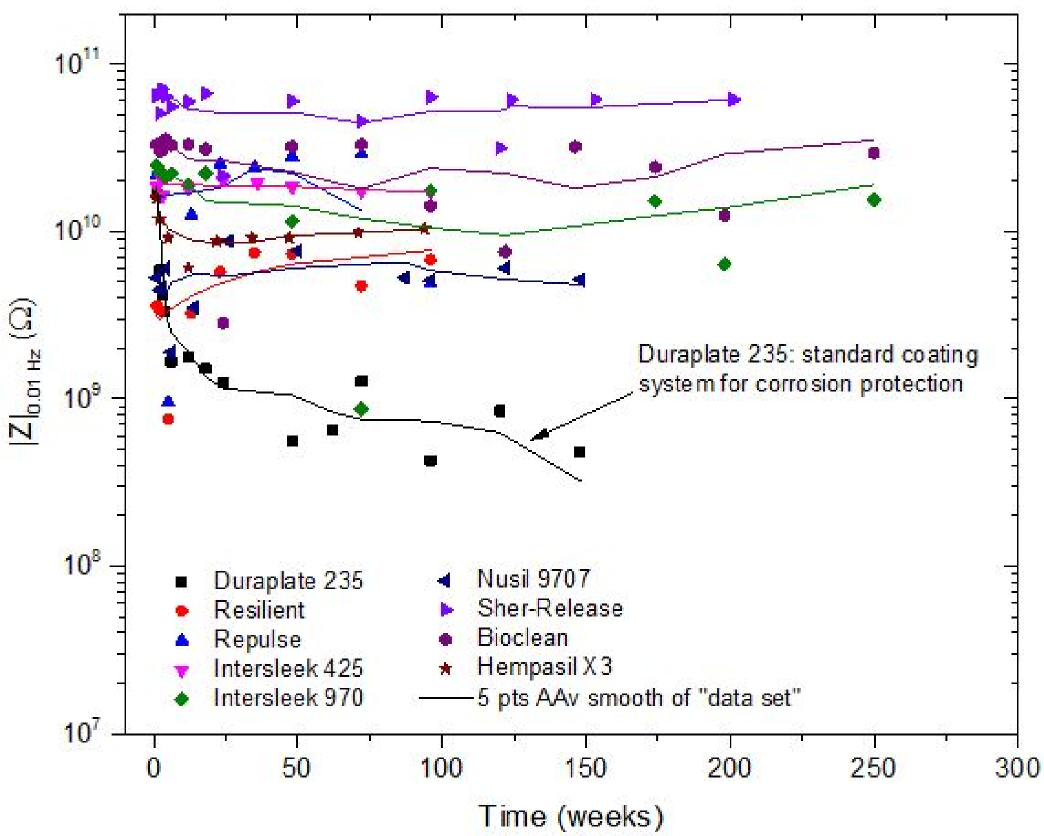

Figure 20.—Impedance magnitude at 0.01 Hz plotted versus cumulative exposure time in weeks; raw data is shown as well as a smoothed line (5 point adjacent averaging).

A high flow rate test using deionized water was conducted using a reservoir tank, polyvinyl chloride (PVC) piping, and a 7.5-horsepower pump as shown in figure 21 to produce flow rates of 95 gallons per minute. Details of the test configuration are presented in table 3.

Figure 21.—High flow water test set up. Samples are placed inside 1.5 in PVC pipe.

Table 3.—High Flow Test Parameters

Pump	Piping	Test conditions	Test duration
7.5 HP 3,450 RPM 3-inch discharge Flow rate: 95 gallons per minute (measured)	1.5" schedule 40 PVC	Velocity: 25–30 ft/s Temp: 75–115 °F Deionized, filtered water	Alternating 2 hours flowing, 22 hours static immersion (approx.) Total: 196 hours flowing, 2928 hours static

The water velocity would vary inversely with the cross sectional area and would accelerate in locations where the pipe was partially obstructed due to the presence of samples. The velocity across the samples was estimated to be between 25 to 30 ft/s. This test simulates the flow rates seen in penstocks, outlet works, and various pipelines found throughout Reclamation infrastructure.

High flow immersion tests were performed on three (3) FR coating systems, which are shown in table 4. Samples sizes were 1- by 6-in length on 1/8-in thick steel. Two (2) panels were coated with 1/16- to 3/32-in of coal tar enamel by Lone Star Specialties in accordance with American Water Works Association (AWWA) C203 Type II [23]. The coal tar enamel was prepared using a sweep blast SSPC-SP7 technique of a coal slag abrasive to create an aggressive profile [24]. A third panel was prepared to SSPC SP5 white metal blasted steel with a three (3) mil surface profile [25]. The coal tar enamel samples were coated with one (1) to two (2) coats of primer, tie coat, and a foul-release top coat in such a manner as to leave approximately one (1) centimeter of each coat exposed.

Table 4.—Systems Tested for Overcoating Coal Tar Enamel

System	Existing Substrate	Primer	Tie Coat	Top Coat
1	Coal tar enamel	Duraplate 301K	Sher-Release Tie Coat	Sher-Release
2	Coal tar enamel	Enviroline 376F	Intersleek 731	Intersleek 970
3	Coal tar enamel	Amercoat 240/ Sigmashield 620	Sigmaglide 790	Sigmaglide 890

The pump on the high flow immersion test was run each day for approximately two (2) hours. The water temperature in the tank rose from 65 °F to 105 °F. On a few occasions the pump was run for longer and the water temperature reached 118 °F.

All three (3) coating systems used to overcoat coal tar experienced failures in the high flow test. Typically, the coal tar experienced a disbondment from the metallic substrate on the overcoated portion as shown in figure 22. Neither static immersion in a dilute Harrison solution or in deionized water produced catastrophic failure, but cracking was observed in several samples along the interface between coal tar enamel and the primers. It was believed that internal stresses, perhaps due to expansion/contraction of the primer and subsequent layers, caused the low strength coal tar enamel to fail. It was unlikely this problem was unique to foul-release coating systems, but the extra coats that were required may aggravate the effect.

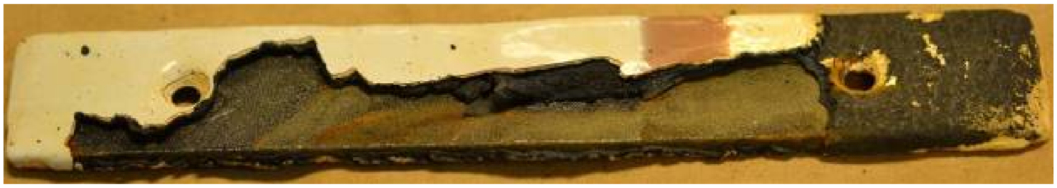

Figure 22.—Failure of overcoated coal tar during a high flow test.

CONCLUSION

MERL has screened more than 100 materials and coating systems for fouling prevention. The field testing identified foul-release coatings that prevent mussels from attaching to surface and Jotun Sealion Resilient provided the best performance of a hard coating tested. Table 1 identified all successful products and a few new experimental technologies that look very promising.

Laboratory tests further evaluated the foul-release coatings for corrosion protection and potential modes of failure due to mechanical damage. Foul-release coatings provide increased barrier properties for corrosion protection and potentially longer service lives by having a slower degradation rate. Foul-release coatings provide better UV stability than epoxy coatings. The degree of corrosion undercutting in the accelerated tests, prohesion, and modified prohesion, were concerning for a few of the coating systems. Foul-release coatings are susceptibility to mechanical damage due to poor abrasion, impact, and gouge resistance. However, foul-release coatings outperform hard coatings when subjected to a slurry erosion test, UV protection, and in metal-on-metal exposure from the trashrack at Parker Dam.

A polyamide epoxy is a commonly used coating system for water immersion environments. The expected service life of an epoxy will depend on a variety of factors, but is estimated to be about 15 to 20 years. Ideally, a successful foul-release coating would last as long as an epoxy or longer.

It is important for the specifier to know and thoroughly understand the environmental conditions of the infrastructure prior to selecting the correct products. All FR coatings, hard and soft, have limitations. Successful deployment of FR coating will depend strongly on the service environment. None of the coating systems are recommended for application over coal tar enamel.

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Appendix

Complete
Materials Testing Log:
Years 2008-2015

	Generic Name or Trade Name	Dates Tested	Durable Yes/No	Max Force to Remove Mussels (lb)	Most Recent Blockage or Coverage (for plates)	Comments
1	100% Zn Metallizing	05-2008 to 12-2008	Yes	N/A 1st year	50%	Many mussels
2	2012-MTA-8-1003-1	12/2012 to present	Yes	0.147	0% Coverage (3"x6" Plate)	No mussels, algae, sponges, and plants
3	2012-MTA-8-1003-2	12/2012 to present	Yes	0.00	0% Coverage (3"x6" Plate)	No mussels, algae, sponges, and plants
4	2012-MTA-8-1003-3	12/2012 to 5/2014	Yes	0.30	100% Coverage (3"x6" Plate)	Many mussels, low release force
5	2012-MTA-8-1003-4	12/2012 to 5/2014	Yes	0.28	100% Coverage (3"x6" Plate)	Many mussels, low release force
6	2012-MTA-8-1004-1	12-2012 to 12-2013	No	0.40 (p)	40% Coverage (3"x6" Plate)	Many mussels, many blisters
7	2012-MTA-8-1004-2	12-2012 to 12-2013	No	1.96 (p)	100% Coverage (3"x6" Plate)	Fully fouled
8	2012-MTA-8-1004-3	12-2012 to 12-2013	No	1.55 (p)	100% Coverage (3"x6" Plate)	Fully fouled
9	2012-MTA-8-1004-4	12-2012 to 12-2013	No	0.96 (p)	100% Coverage (3"x6" Plate)	Fully fouled
10	2012-MTA-8-1005-1	12-2012 to 12-2013	Yes	0.58	100% Coverage (3"x6" Plate)	Fully fouled
11	2012-MTA-8-1005-2	12-2012 to 12-2013	Yes	0.98	100% Coverage (3"x6" Plate)	Fully fouled
12	2012-MTA-8-1005-3	12-2012 to 12-2013	Yes	1.15	100% Coverage (3"x6" Plate)	Fully fouled
13	2012-MTA-8-1005-4	12-2012 to 12-2013	Yes	0.43	100% Coverage (3"x6" Plate)	Fully fouled
14	2012-MTA-8-1005-5	12-2012 to 12-2013	Yes	0.58	100% Coverage (3"x6" Plate)	Fully fouled
15	304 Stainless Steel	06-2010 to 05-2012	Yes	1.75	100%	Fully fouled
16	3M Lexzar V Maxx	11-2011 to 12-2012	Yes	1.60	86%	Fully fouled
17	85-15 Zn Al Metallizing	05-2008 to 12-2008	Yes	N/A 1st year	75%	Fully fouled
18	90-10 copper nickel	08-2008 to 12-2008	Yes	N/A 1st year	100% Coverage (12" plate)	Fully fouled
19	Aquafast	08-2011 to 05-2012	Yes	0.95	N/A (3"x6" plate)	Moderate mussel fouling, algae present
20	Aquafast Experimental	08-2011 to 05-2012	Yes	0.83	N/A (3"x6" plate)	Moderate mussel fouling, algae present
21	Aqualastic	05-2009 to 1-2010	Yes	0.32	67%	Many mussels
22	AS&M Aerokret 12XS	12-2012 to 12-2013	Yes	0.28	86%	Fully fouled
23	AS&M Aerokret 21XS	12-2012 to 12-2013	Yes	0.40	87%	Fully fouled

	Generic Name or Trade Name	Dates Tested	Durable Yes/No	Max Force to Remove Mussels (lb)	Most Recent Blockage or Coverage (for plates)	Comments
24	Battelle	10-2009 to 11-2010	Yes	0.77	55% (12" plate)	Many mussels
25	Bayer	11-2010 to 5-2012	Yes	0.28	100%	Fully fouled
26	Bioclean Black	10-2009 to present	No	0.173	64%	No mussels, some algae, slime, and plants, self cleaning
27	Bioclean White	10-2009 to present	No	0.00	N/A (3"x6" plate)	No mussels, self cleaning
28	Brass	05-2008 to 11/2010	Yes	1.31	62% (12" plate)	An occasional mussel, some slime
29	Bronze	05-2008 to 5/2014	Yes	1.37	18% (12" plate)	Moderate mussel colonization
30	Cathacoat 304	05-2008 to 12-2008	Yes	N/A 1st year	100%	Fully fouled
31	Cathacoat 304L	05-2008 to 12-2008	Yes	N/A 1st year	75%	Fully fouled
32	Cathacoat 313	05-2008 to 12-2008	Yes	N/A 1st year	100%	Fully fouled
33	Ceilcote 222	10-2009 to 11-2010	Yes	0.53	100%	Fully fouled
34	Coal tar enamel	5-2011 to 5-2012	Yes	0.64	17.5% (12" plate)	Fully fouled
35	Copper	05-2008 to 5/2014	Yes	1.41	5% (12" plate)	A few mussels, some slime
36	Curex	12-2008 to 05-2009	Yes	N/A 1st year	10%	Few mussels, blistered and corrosion
37	Dap Black	3-2013 to 12-2013	No	0.37	70%	Fully fouled
38	Du Slip	11-2011 to 12-2012	Yes	1.60	71%	Fully fouled
39	Duraplate 235	5-2010 to 5-2011	Yes	1.40	87%	Fully fouled
40	Durashield	11-2011 to 12-2012	Yes	0.94	100%	Fully fouled
41	Duromar HPL-2221LSE	11-2010 to 11-2011	Yes	1.07	39%	Many mussels, blistered
42	Duromar HPL-2510FR	11-2010 to 11-2011	Yes	0.76	41%	Many mussels
43	ECTFE	05-2009 to 1-2010	Yes	0.41	44%	Many mussels
44	E-Paint SN-1	05-2008 to 12-2008	No	N/A 1st year	25%	Many mussels
45	E-Paint Sunwave plus	05-2008 to 05-2009	Yes	N/A 1st year	25%	Many mussels
46	E-Paint ZO-HP	05-2008 to 12-2008	No	N/A 1st year	20%	Many mussels
47	ETFE	05-2009 to 1-2010	Yes	0.43	51%	Many mussels
48	FEP	05-2009 to 1-2010	Yes	0.47	46%	Many mussels
49	Fuji (Black)	05-2009 to present	No	0.00	9%	No mussels, some algae, slime,

	Generic Name or Trade Name	Dates Tested	Durable Yes/No	Max Force to Remove Mussels (lb)	Most Recent Blockage or Coverage (for plates)	Comments
						and plants. Self-cleaning
50	Fuji + Duraplate	06-2010 to 11-2011	No	0.00	6%	No mussels. Self-cleaning
51	Fuji Fish Screen	05-2009 to present	No	0.00	N/A (Screen)	No mussels, some algae, slime, and plants. Self-cleaning
52	Fuji Oil Free	7-2012 to present	No	0.00	5%	No mussels self-cleaning
53	Fuji Sept 2010 Formulation	03-2011 to present	No	0.00	18%	No mussels. Self-cleaning
54	Fuji Tie + Duraplate	06-2010 to 11-2011	No	0.25	30%	Many mussels, some algae, slime, and plants
55	Fuji White	08-2008 to present	No	0.00	3%	No mussels. Self-cleaning
56	Galvanized Steel	05-2008 to 12-2008 and 5/2010 to 5/2012	Yes	1.463	79%	Fully fouled
57	Hanson	11-2011 to 12-2012	Yes	0.651	100%	Fully fouled
58	Hempel: Hempasil X3	12-2012 to present	No	0.00	2%	No mussels, some algae self-cleaning
59	Hullspeed	11-2011 to 12-2012	Yes	0.69	54%	Many mussels present
60	International Paint: Intersleek 425	12-2012 to present	No	0.00	3%	No mussels, some algae self-cleaning
61	Intersleek 970	05-2008 to present	No	0.25	9%	Few mussels, mostly on damaged area. Self-cleaning
62	Jotun Sealion Repulse	5-2013 to present	No	0.00	2%	No mussels, self-cleaning
63	Jotun Sealion Resilient	5-2013 to present	Yes	0.19	5%	Some mussels, algae, plants, slime, sponges. Potentially self-cleaning
64	Lumiflon	10-2009 to 11-2010	Yes	1.74	100%	Fully fouled
65	Luminore	05-2008 to 5/2014 (plates) 5-2008 to 5/2010	Yes	1.1	29%	Many mussels. Service life in static 6 years, dynamic 18 months
66	Novacoat 2000 PW	08-2008 to 12-2008	Yes	N/A 1st year	50% (12” Plate)	Many mussels
67	Nusil 9707	5-2012 to present	No	0.46	7%	No mussels, self-cleaning
68	Nusil R 1082	5-2013 to 12-2014	Yes	0.20	86%	Fully fouled, low release force

	Generic Name or Trade Name	Dates Tested	Durable Yes/No	Max Force to Remove Mussels (lb)	Most Recent Blockage or Coverage (for plates)	Comments
69	Nusil: 9706	5 2012 to 12-2012	No	N/A (Coating delam)	0%	Coating delaminated from primer
70	Permadri	08-2008 to 12-2008	Yes	N/A 1st year	25%	Many mussels, blistered
71	Permatex Black	5-2013 to 12-2013	No	2.24 (plow)	100% Coverage (3"x6" Plate)	Fully fouled
72	Permatex Blue	5-2013 to 12-2013	No	2.35 (plow)	100% Coverage (3"x6" Plate)	Fully fouled
73	Permatex Clear	5-2013 to present	No	0.00	0 Coverage (3"x6" Plate)	No mussels some algae, plants
74	Permatex Gray	5-2013 to 12-2013	No	0.60 (plow)	100% Coverage (3"x6" Plate)	Fully fouled
75	Permatex Red	5-2013 to present	No	0.00	20% Coverage (3"x6" Plate)	No mussels, some algae, plants
76	PFA	05-2009 to 05-2010	Yes	0.20	48%	Many mussels
77	Phasecoat	11-2010 to 11-2011	No	0	5%	Poor lab test performance
78	Plasite 4500S	05-2008 to 12-2008	Yes	N/A 1st year	66%	Fully fouled
79	Plasite 9145 TFE	10-2009 to 11-2010	Yes	0.61	100%	Fully fouled
80	Polyglycolic acid	7-2012 to 12-2013	Yes	0	N/A (3x6 Panel)	Few mussels and algae
81	Polyset	5-2013 to 5/2014	Yes	1.08	86%	Fully fouled
82	PPG Sigmaglide 890	10-2009 to present	No	0.552 (p)	40%	Mussels on damaged area. Self-cleaning
83	PVDF	05-2009 to 11-2009	Yes	0.41	25%	Many mussels
84	Rilsan	05-2009 to 11-2009	Yes	N/A 1st year	25%	Many mussels
85	Rylar #1	05-2011 to 11-2012	Yes	0.70	100%	Many mussels, blistered
86	Rylar #2	11-2011 to 12-2012	Yes	1.36	37%	Moderate mussel colonization
87	Seacoat Seaspeed V5/ Amercoat	10-2009 to 11-2011	Yes	0.56	92%	Fully fouled
88	Seacoat Seaspeed V5/ Amerlock	10-2009 to 05-2012	Yes	0.56	72%	Fully fouled
89	Sealife	05-2008 to 12-2008	Yes	N/A 1st year	25%	Many mussels
90	SEI Chemical SHC-500	10-2009 to 11-2010	Yes	0.73	97%	Fully fouled
91	Seicoat GPA 300	5-2012 to 5-2013	No	0.21	85%	Fully fouled, low release force
92	Seicoat GPA 400	12-2012 to 12-2013	Yes	0.34	93%	Fully fouled

	Generic Name or Trade Name	Dates Tested	Durable Yes/No	Max Force to Remove Mussels (lb)	Most Recent Blockage or Coverage (for plates)	Comments
93	Seicoat Nanoxirane	12-2012 to 12-2013	Yes	0.52	95%	Fully fouled
94	Silver Bullet	10-2009 to 11-2010	Yes	1.29	97%	Fully fouled, blistered
95	Steel	05-2008 to 12-2008	Yes	N/A 1st year	100%	Fully fouled
96	Targuard	5-2012 to 12-2012	Yes	1.71	60% Coverage (3”x6” Plate)	Many mussels
97	Tesla	5-2013 to 12-2013	Yes	0.80	56%	Many mussels
98	Trunano	05-2011 to 5-2012	Yes	0.939	86%	Many mussels
99	Wearlon	05-2008 to 12-2008	Yes	N/A 1st year	100%	Fully fouled

Reclamation Experimental Formulations

	Generic Name	Dates Tested	Durable Yes/No	Max Force to Remove Mussels (lb)	Percent Coverage (for plates)
100	Reclamation #1	3/2013 to present	No	0.00	0%
101	Reclamation #2	3/2013 to present	No	0.00	0%
102	Reclamation #3	3/2013 to present	No	0.00	0%
103	Reclamation #4	3/2013 to present	No	0.00	0%
104	Reclamation #5	3/2013 to present	No	0.00	20%
105	Reclamation #6	3/2013 to present	No	0.107	40%
106	Reclamation #7	3/2013 to present	No	0.331	50%
107	Reclamation #8	3/2013 to present	No	0.489	50%
108	Reclamation #9	3/2013 to present	Yes	0.531	90%
109	Reclamation #10	3/2013 to 12/2013	Yes	0.566	50%
110	Reclamation #11	3/2013 to 5/2014	No	0.635	50%
111	Reclamation #12	3/2013 to present	No	0.659	50%
112	Reclamation #13	3/2013 to 12/2013	Yes	0.752	70%
113	Reclamation #14	3/2013 to present	Yes	0.771	90%
114	Reclamation #15	3/2013 to 5/2014	No	0.89	30%
115	Reclamation #16	3/2013 to 12/2013	Yes	1.043	70%
116	Reclamation #17	3/2013 to 12/2013	Yes	1.151	50%
117	Reclamation #18	3/2013 to 12/2013	Yes	1.196	90%
118	Reclamation #19	3/2013 to 5/2014	Yes	1.903	90%

Data sets that support the final report: H:d8180/Coatings/Zebra mussels

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