RECLAMATION
Managing Water in the West

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Coatings for Mussel Control — Results from Six Years of Field Testing

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.

On the cover: Steel plate coated with a silicone oil-free version of Silicone FR #1 after 22 months of immersion in mussel-infested water. Mussels have attached to the back and sides of the plate, but not to the coated surface.

BUREAU OF RECLAMATION
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Acronyms and Abbreviations

ECTFE	polyethylenechlorotrifluoro ethylene
ETFE	polyethylenetetrafluoroethylene
FEP	polyfluoroethylene propylene
ft	feet
in	inch(es)
lb	pound(s)
MERL	Materials Engineering and Research Laboratory
MTA	Material Transfer Agreement
NSF	National Sanitation Foundation
PFA	polyperfluoroalkoxy
PGA	polyglycolic acid
PVDF	polyvinylidene fluoride
Reclamation	Bureau of Reclamation
RTV	room temperature vulcanization

Symbols

°F	degrees Fahrenheit

EXECUTIVE SUMMARY

Since 2008, the Materials Engineering and Research Laboratory (MERL) researchers have evaluated over 100 coatings and materials for mussel control. The materials testing log is presented in the appendix at the end of this report.

This report details the results through six years of testing. Earlier results are shown in the three-year report, which is available online [1].

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 Bureau of Reclamation (Reclamation) equipment. MERL has found a number of silicone-based foul-release coatings that have performed well for controlling mussel attachment, but they have poor resistance to abrasion, gouge, and impact damage. These coating systems do not contain biocides and strictly rely on surface properties to prevent mussel attachment. To date, MERL has not found a commercially available durable foul-release coating that prevents mussel attachment. However, several experimental durable foul-release products have shown promise in preliminary tests, but they have only been exposed for 18 months. One commercial durable foul-release coating also shows promise as a self-cleaning system following 12 months of exposure. Table 1 shows the coatings and metal alloys that have performed well for controlling mussel attachment.

The silicone foul-release coatings are the most promising for deterring mussel attachment in both static (non-flowing) and dynamic (flowing) water conditions. However, the silicones do 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 coatings are considered to be self-cleaning if the drag forces are sufficient to remove fouling under normal operating conditions. Unfortunately, silicone foul-release coatings are soft, lacking abrasion or gouge resistance. Nevertheless, for settings not exposed to impact by heavy debris, these coatings may perform well. Surprisingly, laboratory tests suggest that silicone foul-release coatings have superior erosion resistance compared to epoxy coatings for sediment- and silt-laden waters and, in this respect, are comparable to ceramic epoxies.

Table 1. Materials that prevent mussel attachment or are self-cleaning

Product code	Coating type	Durable Yes/No	Results	Test Duration
Fluorinated Silicone FR	Fluorinated silicone foul-release coating	No	A few mussels attach to the surface, but are removed with very low force, self-cleaning properties	5/2008 to present
Silicone FR #1	Silicone foul-release coating	No	No mussel attachment, only algae and aquatic vegetation	5/2008 to present
Silicone FR #2	Silicone foul-release coating	No	No mussel attachment, only algae and aquatic vegetation	5/2009 to present
Silicone FR #3	Silicone foul-release coating	No	No mussel attachment, only algae and aquatic vegetation	10/2009 to present
Silicone FR #4	Silicone foul-release coating	No	No mussel attachment, only algae and plants. Small blisters formed on the coating after 3 years	10/2009 to present
Silicone FR #5	Silicone foul-release coating	No	No mussel attachment, only algae and aquatic vegetation	10/2009 to present
Silicone FR #7	Silicone foul-release coating	No	No mussel attachment, only algae and aquatic vegetation	5/2008 to present
Silicone FR #9	Silicone foul-release coating	No	No mussel attachment, only algae and aquatic vegetation	3/2011 to present
Silicone FR #11	Silicone foul-release coating	No	No mussel attachment, only algae and aquatic vegetation	5/2012 to present
Silicone FR #12	Silicone foul-release coating	No	No mussel attachment, only algae and aquatic vegetation	12/2012 to present
Silicone FR #13	Silicone foul-release coating	No	No mussel attachment, only algae and aquatic vegetation	12/2012 to present
Silicone FR #16	Silicone foul-release coating	No	No mussel attachment, only algae and aquatic vegetation	5/2013 to present
Silicone FR Oil Free	Silicone foul-release coating	No	No mussel attachment, only algae and aquatic vegetation	7/2012 to current
Silicone Epoxy FR #7	Silicone epoxy FRC	Yes	Mussels and algae do attach, however release with less than 0.20 lbs, potentially self-cleaning	5/2013 to present
2012-MTA-8-1003 #1*	Not disclosed*	Yes	No mussel attachment	12/2012 to present
2012-MTA-8-1003 #2*	Not disclosed*	Yes	No mussel attachment	12/2012 to present
Permatex Red	Automotive RTV silicone gasket	No	No mussel attachment	5/2012 to present
Permatex Clear	Automotive RTV silicone gasket	No	No mussel attachment	5/2012 to present
Copper AF	Copper metal antifouling coating	Yes	Mussel fouling occurred in flowing water after 2 years. No mussels in static water. Blisters formed after 4 years	5/2008 to 5/2014
Copper	Copper metal	Yes	Few mussels	5/2008 to 5/2014
Bronze	Bronze metal	Yes	Few mussels	5/2008 to 5/2014

*MTA – Material Transfer Agreement, experimental coating system

Since most silicone foul-release coatings contain a silicone oil-release additive, MERL tested a silicone oil-free version of Silicone FR #1 to determine if the mussels would attach once the oils were depleted. The results showed no mussel attachment after 22 months of exposure. (See cover photo.) The coating manufacturers use silicone oils as release agents to assist fouling release of marine organisms. Since silicone oil is designed to be consumed by leaching from the coating, foul-release performance would typically degrade over time. If oil-free coatings are effective in freshwater environments, foul-release capability may be maintained throughout the life of the coating. MERL's finding shows that the principles of foul-release coatings for marine fouling may not apply directly with freshwater fouling. Furthermore, removing the silicone oil from the formulation could provide coating manufacturers with lower-cost coatings as well as a better National Sanitation Foundation (NSF 61) approval rating for drinking water [2].

Most durable foul-release coatings evaluated by MERL allow mussels to attach to the coating surface. The mussels build up significantly and cause nearly 100 percent blockage of flow through the coated grates. Although the mussels attach with varying strength, they remain attached to the surface without being released under the test conditions, i.e. they are not self-cleaning. The durable foul-release systems that are currently being evaluated are Silicone Epoxy FR #7 and 2012-MTA-8-1003 #1 and #2. It is premature to make any final conclusions regarding the effectiveness of these systems. Silicone Epoxy FR #7 allowed mussel attachment but was easily cleaned with less than 0.20 pounds of force for the first 12 months of exposure. The two experimental formulations from the Material Transfer Agreement partner (2012-MTA-8-1003) prevented mussel attachment for the first 18 months of exposure.

During 2011 and 2012, Reclamation's Hydraulic Investigations and Laboratory used submerged waterjets to evaluate cleanability. During testing, researchers observed that the byssal threads remained attached to the surface of every hard coating or metal, including stainless steel, coal tar enamel, coal tar epoxy, polyamide epoxy, and durable foul-release coatings [3]. Plates with significant mussel attachment were left with byssal threads that could not be removed with the waterjet. Even a spot jet close to the surface was ineffective at completely removing the byssal threads. While it is undesirable to have threads remaining on the surface of the coating, it may not be necessary to have them completely removed, as they do not significantly increase flow friction or head differential. The waterjetting study showed that durable foul-release coatings evaluated offered no advantage over a conventional epoxy or coal-tar enamel because it was not any easier to clean the mussels from the coating surface. The full report, *Resistance of Protective Coatings to High Pressure Water Jets for Invasive Mussel Removal*, is located at:
http://www.usbr.gov/pmts/hydraulics_lab/pubs/PAP/PAP-1074.pdf

INTRODUCTION

Zebra mussels were first discovered in the United States in the 1980s in the Great Lakes. Since then, both zebra and quagga mussels have spread rapidly across U.S. lakes and river systems. In January 2007, quagga mussels were found in Lake Mead (the reservoir created by Hoover Dam). Since then, the mussels have spread downstream into the Colorado aqueduct as well as the Central Arizona Project. Detections of zebra and quagga mussels have also been confirmed 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 to create long-term economic impacts. Mussels attach to underwater surfaces and can clog small-diameter piping (i.e., cooling water; heating, ventilation, and air conditioning; and domestic water piping), reduce flow in larger diameter piping, clog fish screens, and impact intake structures. The flowing water conditions create a more favorable environment for attached mussels to thrive.

Due to the potential impacts that mussels have at Bureau of Reclamation (Reclamation) facilities, a coatings research project was started in 2008 to identify solutions to the problems caused by mussels.

Most of the commercial products tested thus far have been marketed for fouling control in the marine shipping industry. However, the service environment at Reclamation facilities presents some unique challenges that must be considered when evaluating a fouling control coating: highly variable water quality and abundant waterborne materials that affect durability, including sediment loads, woody debris, vegetation, ice, and other debris. Also, while it is common to recoat ship hulls every 5-6 years, Reclamation infrastructure is less accessible and requires a longer service life. Therefore, these commercially available products were evaluated to determine if they could meet Reclamation's needs. In addition, most commercial products have been formulated and tested to deter all marine fouling organisms, such as barnacles and tubeworms (not zebra and quagga mussels). Prior to this study, Reclamation did not have a compelling need for coatings to address biofouling problems.

This report provides a summary of the results from all six years of field testing. Earlier results are detailed in a prior Reclamation report [1].

FIELD TEST SITE

Parker Dam (Figure 1) was selected as the field test site to evaluate coatings in quasi-static (low-flowing) and dynamic (flowing) exposure conditions. The mussels at this location reproduce almost year-round and have a very high growth rate. 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 spacings was tied off with two nylon ropes to prevent twisting and lowered to a depth of 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 SSPC SP1 solvent cleaning and abrasive blast cleaning to an SSPC SP10/NACE 2 near-white metal blast with a 3.0-mil surface profile [4, 5]. 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 from the face of Parker Dam.

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

Several sets of experimental controls were used to determine fouling rates, including epoxy-coated steel, ASTM A788 steel (Figure 4) and 304 stainless steel [6, 7].

Figure 4. Uncoated steel after 7 months of exposure in dynamic conditions. Test period May 2008 to December 2008.

ENVIRONMENTAL CONDITIONS

The water-velocity measurements were recorded in January 2010 and again in June 2010. Veligers were sampled and analyzed from January 2010 through September 2011. The water temperature data has been measured for many seasons, with typical lows around 50°F and highs around 82°F. The data can be found in the Materials Engineering and Research Laboratory (MERL) Report 2012-11 [1].

EXPERIMENTAL PROCEDURES

Following deployment, each coating system was evaluated approximately every 6 months, 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 photographed and cleaned after every evaluation. Since mussel reproduction rates may vary from season to season and from year to year, control substrate monitoring helps to provide an estimate of the extent of fouling during the test duration.

Force Measurements

Mussel attachment strength was determined using a handheld force gage (Shimpo Model FGV-5XY, maximum capacity of 5 lb). The procedure was modeled after ASTM D 5618-94, which is used to determine the attachment strength of barnacles [8]. The technique involves using a probe to gradually apply a shear load to the mussel. The peak force recorded by the gage was taken as the attachment force. The main difference 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 measure the number of byssus threads that were attached to the surface in the field. Therefore, measurements are absolute forces and cannot 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 inches 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.

RESULTS AND DISCUSSION

Silicone and Fluorinated Silicone Foul-Release Coatings

The silicone foul-release coatings (Silicone FR #1 through #16) and Fluorinated Silicone FR can become fouled, but this was primarily due to the accumulation of algae, biofilm, and aquatic plants. Mussels can attach to these species and make it look like the mussels are firmly attached. However, the aquatic weeds wrap on the leading edge or cross members and only give the appearance that the grate was fouled. Quagga mussels do not physically attach to the silicone foul-release surfaces and in most cases require little or no force for removal, as seen in Figure 5. The only exceptions were Silicone FR #14 and 15, which did allow mussels to attach to the surface. Most silicone and fluorinated silicone foul-release coatings showed releases once fouling had built up enough for drag forces to exceed the bond strength and peel the fouling material from the surface. Another possible explanation of the self-cleaning phenomenon is that during the summer months flow rates, and hence velocities, are higher due to an increased power demand (peaking power) and water demand for irrigation. This subjects the fouling organisms to greater shear forces. In general, there was significantly less fouling on the silicone and fluorinated silicone foul-release coatings in the fall inspections than during the spring inspection. Water velocities during the summer months ranged from 1.8 to 2.4 feet per second across the trash rack structure. During the winter months water velocities were 0.15 to 0.5 feet per second.

In general, the silicone and fluorinated silicone foul-release coatings have been successful thus far in preventing or minimizing fouling. Limitations are foreseen for situations in which debris is present in the water that will rub, abrade, or gouge the coating. These coating systems should work well on infrastructure that is unaffected by such debris.

Silicone Foul-Release Coatings Withdrawn from Study

In December 2012, Silicone FR #10 was withdrawn from the study due to poor adhesion between the primer and topcoat; the topcoat delaminated in the test, and mussels attached to the underlying epoxy primer.

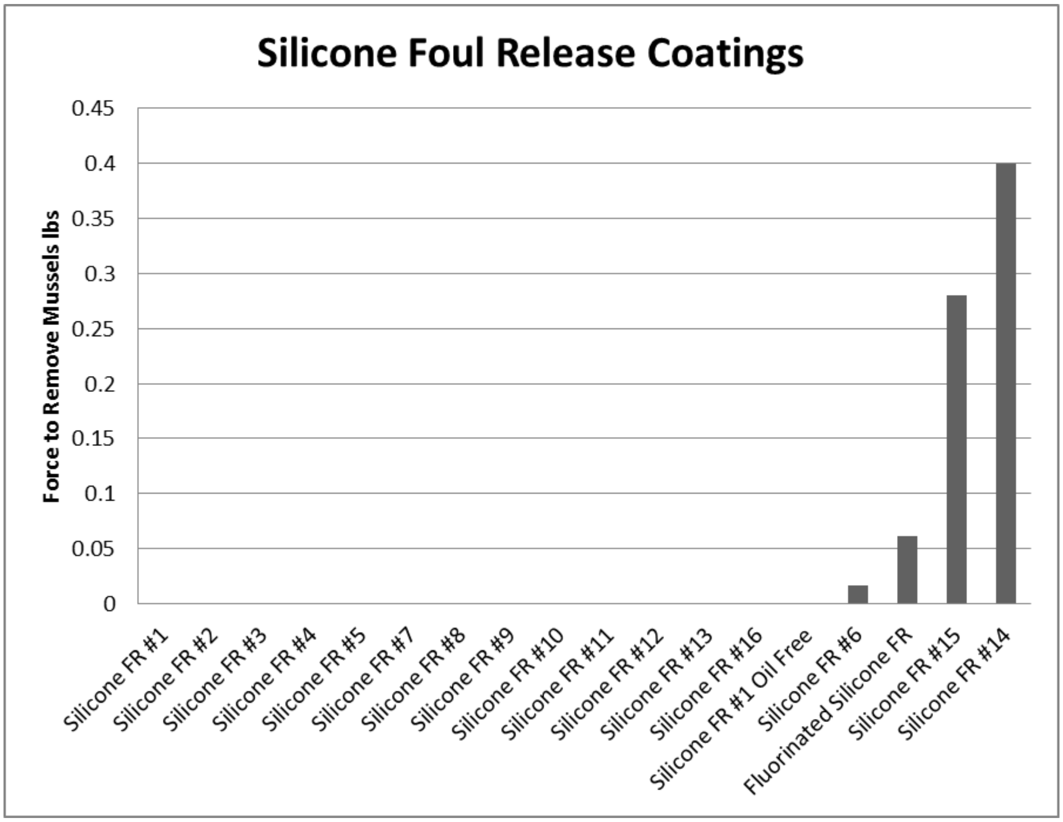

Figure 5. Force measurements for silicone and fluorinated silicone foul-release coatings.

Silicones FR #14 and #15 were withdrawn from the study due to mussel attachment and were not able to self-clean. The mussels caused 100-percent blockage of the coated floor grates in flowing conditions. Silicones FR #14 and #15 were designed as erosion-resistant silicone coatings (higher modulus), but the manufacturer stated that the products would resist quagga mussel attachment. The products were easily cleaned, requiring 0.25 to 0.4 pounds of force to remove mussels, but were not self-cleaning.

Silicone Foul-Release Theory

The silicone foul-release coatings work is 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 effectively. The low modulus causes the macro-fouling to release in a peeling mode rather than in shear. The peeling mechanism requires less force for removal than a shearing mechanism [9-13].

The literature suggests that silicone foul-release coatings function by interfering with the adhesion of marine fouling organisms, but some hydrodynamic flow is required to cause the release to occur [14]. MERL experience has shown foul-release performance to be equivalent 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 2014, several silicone foul-release coatings had been exhibiting mussel-free performance for durations in excess of 6 years.

Commercially available silicone foul-release 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 maintain oil on the surface for as long as possible, but eventually the oil becomes depleted. The performance typically degrades over time in the marine environment. MERL researchers questioned whether the silicone oil additive was essential for foul-release efficacy. The manufacturer of Silicone FR #1 agreed to provide an oil-free version for testing purposes, which was placed in testing in July 2012. The silicone foul-release coatings without silicone oil did not allow mussel attachment to the surface (shown on Figure 6 and the front cover). This new discovery may allow coating manufacturers to develop coatings with NSF 61 approval ratings for drinking water [2]. This also suggests that as long as the silicone foul-release coatings are not damaged, they will perform for the life of the coating. MERL's discovery suggests that foul-release coatings work differently in freshwater than in marine settings. This revelation could lead to the formulation of foul-release coatings designed specifically for freshwater immersion, which are better able to meet the needs of Reclamation and the industrial maintenance market.

Figure 6. Silicone oil-free version of Silicone FR #1 after 22 months of exposure.

Durable Foul-Release Coatings

For purposes of this report, "durable" is defined as resistance to mechanical damage during typical handling, installation, inspection, and maintenance procedures. For instance, handling of a freshly coated structure using wide nylon straps would abrade and rub the silicone foul-release coatings down to the epoxy primers. Damage would occur prior to the structure being placed in service. These damaged areas would accumulate mussels.

The durable foul-release coatings described in this section would resist damage during handling, installation, inspection, and maintenance procedures; it doesn't necessarily mean that these coatings could withstand the environment they are subjected to. For instance, mechanical damage still will occur on a freshly coated trashrack that is constantly raked by a metal trashrake. All coatings would eventually fail under these conditions, including epoxies, polyurethanes, and coal tar enamel. One should not expect foul-release coatings or durable foul-release coatings to withstand these conditions.

Most durable foul-release coatings that MERL tested allow mussels to attach to the coating surface with varying amounts of force, as shown in Figure 7. 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 generally are not self-cleaning. The only exceptions among the systems currently being evaluated are Silicone Epoxy #7 and 2012-MTA-8-1003 #1 and #2. It is premature to make any conclusions regarding the effectiveness of these systems. Silicone Epoxy #7 allowed mussel attachment requiring 0.2 lbs of force to remove a mussel, but appears to be self-cleaning for the first 12 months of exposure, as shown in Figure 8. The two experimental formulations from the Material Transfer Agreement (MTA) prevented mussel attachment, for the first 18 months of exposure, as shown in Figure 9. In that image, mussels are attached to the backs of the panels and to zipties between the panels. In places, chains or "curtains" of mussels anchored on the backs of the panels wrap around to the front side. Up to this point, self-cleaning and prevention of attachment was only observed for silicone and fluorinated silicone foul-release systems. All other durable foul-release coatings evaluated allowed mussel attachment, as described in Table 2. The coatings listed in Table 2 would be easier to clean than a traditional epoxy coating, according to the force measurements. The self-cleaning property was not observed with the durable foul-release coatings listed in Table 2.

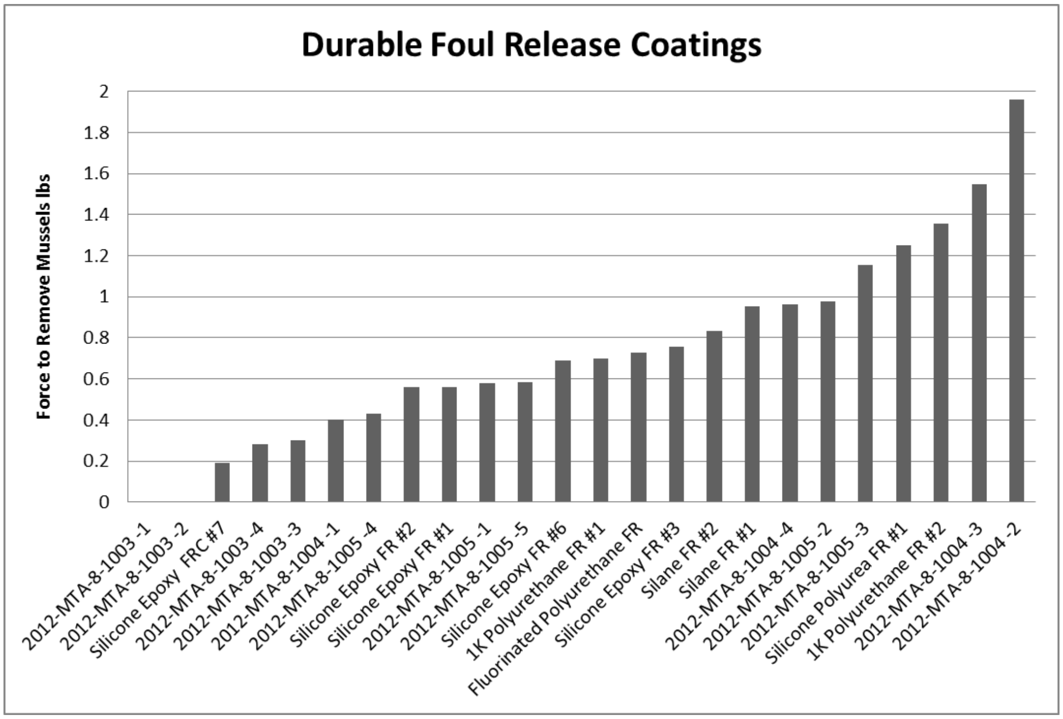

Figure 7. Force measurements for durable foul-release coatings.

Figure 8. Grate coated with Silicone Epoxy #7, as seen in December 2013 (left) and in May 2014, after 1year of exposure (right).

Figure 9. Panels coated with experimental formulations from 2012-MTA-8-1003 #1 and #2, exposure at 18 months.

Table 2. Durable foul-release coatings evaluated for waterjet cleanability

Product code	Mussel attachment strength (lb)	Percent blockage of grate	Waterjet cleaning results
Silicone Epoxy FR #1	0.55	50	Shells were removed, leaving behind the byssal threads on the coating surface
Silicone Epoxy FR #2	0.55	50	Shells were removed, leaving behind the byssal threads on the coating surface
Silicone Epoxy FR #3	0.76	40	Shells were removed, leaving behind the byssal threads on the coating surface
1K Polyurethane FR #1	0.70	100	Shells were removed, leaving behind the byssal threads on the coating surface

In 2011 and 2012, the Hydraulic Investigations and Laboratory performed a cleanability study including some of the durable foul-release coatings listed in Table 2. They discovered that the byssal threads remained on the surface of every hard coating or metal, which included stainless steel, coal tar enamel, coal tar epoxy, polyamide epoxy, and the durable foul-release coatings [3]. Plates with significant mussel attachment were left with byssal threads and sometimes entrails, which could not be removed with the waterjet (as seen in Figure 10). Even using a spot jet close to the surface was ineffective at completely removing the byssal threads. 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 significantly increase flow friction or head differential. The waterjetting study suggested that the durable foul-release coatings tested offer no advantage over a conventional epoxy or coal tar enamel in situations where waterjet cleaning is expected to be utilized.

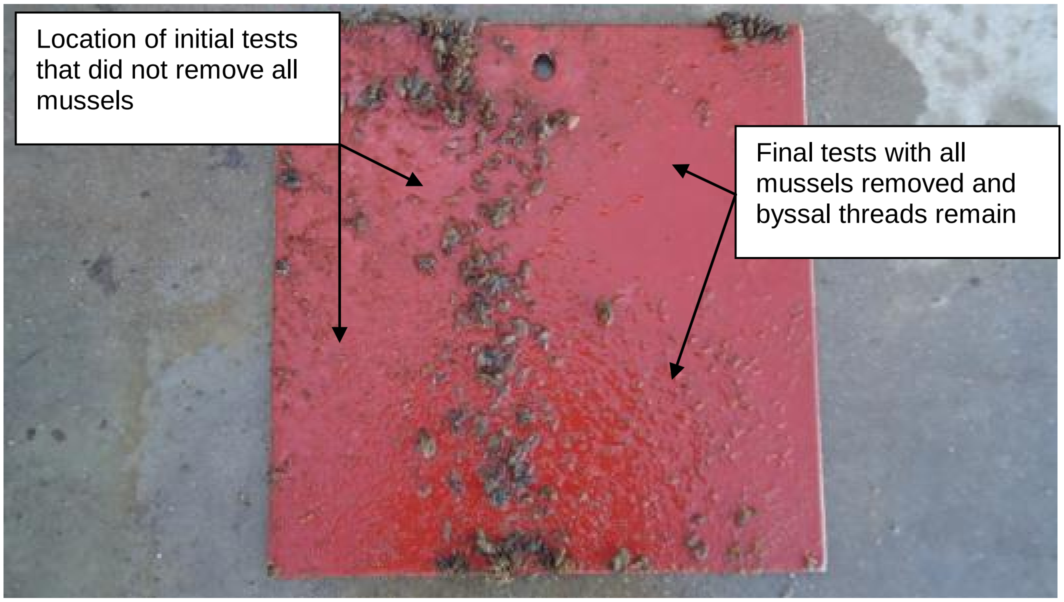

Figure 10. Silicone Epoxy FR #1 sample after release pressure testing.

Low Coefficient-of-Friction Coatings

Low coefficient-of-friction coatings were not designed to prevent mussel attachment; however, MERL has found that some of them have lower release force than the most of the durable foul-release coatings. Figure 11 shows the release force for mussels of various low coefficient-of-friction coatings. Even though these coatings have low release forces, the coatings allow the 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.

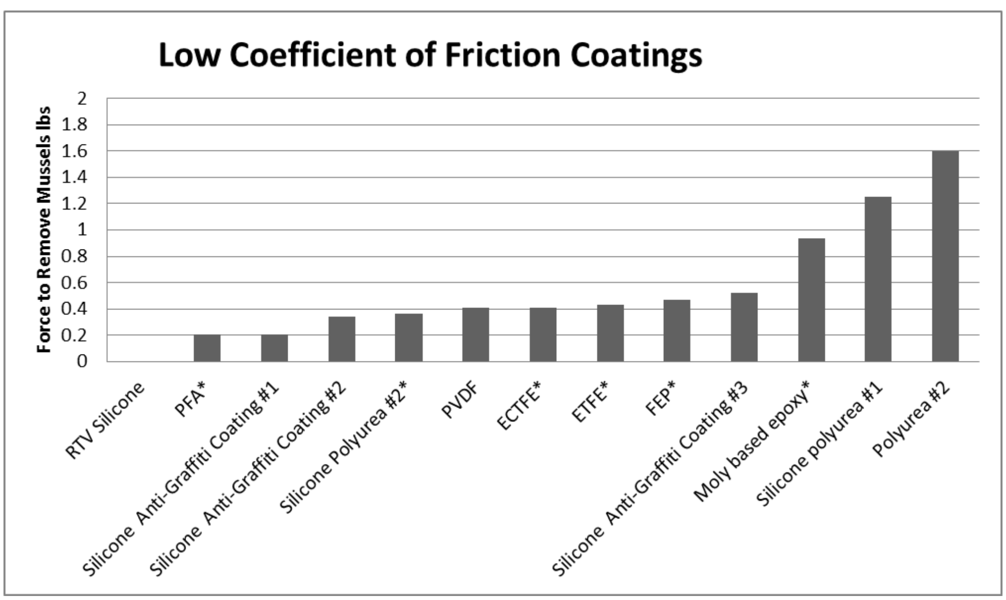

Figure 11. Force measurements for low coefficient-of-friction coatings.

Fluorinated Powder Coatings

MERL evaluated five fluorinated powder coatings. These coatings were not designed as foul-release coatings but rather as "non-stick" coatings. The coatings evaluated were polyvinylidene fluoride (PVDF), polyethylenechlorotrifluoro ethylene (ECTFE), polyethylenetetrafluoroethylene (ETFE), polyfluoroethylene propylene (FEP), and polyperfluoroalkoxy (PFA). Mussels attached to all of these coating systems. Approximately 0.40 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 precipitating onto surfaces. Polyurea #2 and Silicone Polyurea #2 (evaluated from November 2011 to December 2012) had mussel attachment and required 1.6 lb and 0.35 lb, respectively, for removal. Polyurea #2 allowed 90-percent blockage, and Silicone Polyurea #2 allowed 100-percent blockage in 1 year. MERL is also currently evaluating a room temperature vulcanization (RTV) Silicone anti-ice coating; mussels attach to the surface, but require extremely low force for removal. The force was non-detectable for a single mussel and less that 0.40 pounds for a cluster of mussels. The RTV Silicone is tougher than the silicone foul-release coatings, and the entire byssal thread is easily removed during manual cleaning (see Figure 12). The RTV Silicone is not self-cleaning under the testing conditions, but might be useful for infrastructure that has cleaning equipment, such as fish screens, or on other infrastructure that has slightly higher flow rates. Unfortunately, the RTV Silicone studied does not meet Federal standard VOC requirements for industrial maintenance coatings and cannot be recommended for use. The RTV Silicone has provided some important insight for understanding the mussel attachment mechanism.

Silicone Anti-Graffiti Coating

Silicone Anti-Graffiti coatings #1, #2, and #3 are silicone-based coating systems. They are primarily used in an atmospheric environment. Anti-graffiti #1 has approximately the same durability as the silicone foul-release coatings, whereas Silicone Anti-Graffiti #2 and #3 are significantly more durable. The mussels and aquatic plants attached to the coated grate, resulting a blockage of roughly 85 percent. The force to remove the fouling was very low for #1 (0.21 lbs) but moderate for #2 (0.3 lbs) and #3 (0.5 lbs). The products were removed from testing after 1 year.

Molybdenum-Disulfide Containing Coating

MERL evaluated a molybdenum-disulfide based epoxy coating (Moly-based Epoxy) from November 2011 to December 2012. The grate was 100 percent blocked, and 0.9 lbs of force was required to remove mussels.

Figure 12. Grate treated with RTV Silicone ice phobic coating, before cleaning (left) and after cleaning (right), May 2014.

Antifouling Paints

Antifouling paints contain biocides to prevent fouling. All of the antifouling paints evaluated had a limited service life of 1 to 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 nontoxic silicone foul-release coatings. Additional antifouling coatings will only be evaluated if the manufacturer can prove there are no environmental or ecological impacts, from biocides, on freshwater species.

A copper metal antifouling paint (Copper AF) was evaluated beginning in 2008. The mussels did not attach in flowing water for 1 year. After the second year, the grate was blocked about 29 percent with mussels and was withdrawn at the 2-year inspection in 2010. It required 0.85 lb of force to remove a single mussel. The coated substrates in quasi-static water were mussel-free up to 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 was found that was 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 lb of force. The brass began having heavy mussel attachment in May 2010 after 2 years in immersion. The mussels did not adhere to copper nearly as well, requiring only 0.3 lb of force for removal. Copper was more effective than brass or bronze and remained essentially free of mussels after 6 years of testing. The original copper thickness was 0.125 inches and, after 6 years, it measured 0.11 inches. 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 of 1.25 mils per year 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 4 months of exposure.

Zinc-Rich Primers

Reclamation 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 months of exposure [15]. All samples failed to meet the criteria and were removed after 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 [15]. However, under dynamic conditions high densities of quagga mussels attached to the metallic coated grates, causing 50 to 100 percent blockage after 7 months [15]. All samples were removed after 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 [16]. 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, but they were easily removed, requiring no measurable force, similar to the silicone foul-release coatings. There was only one mussel that attached to the PGA surface, and it required 0.245 lb 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.

Material Transfer Agreements

In December 2012 MERL began evaluating experimental coating systems because it appeared that the commercially available durable foul-release systems were not preventing mussel attachment. The Research Office signed three separate MTAs in 2012 to evaluate a total of 14 experimental formulations and two MTAs in 2014 for an additional five formulations. At this time, MERL cannot disclose the identities of the MTA partners, which will referenced by their respective MTA numbers.

Partner 2012-MTA-8-1003 provided four different experimental formulations. As shown in Figure 9, samples #1 and #2 have thus far prevented mussel attachment, after 18 months of exposure. Samples #3 and #4 had mixed results: some of the panels did not have any mussels while other replicates had mussels covering the entire surface. Both sets had very low release forces to remove clusters: sample #3 required 0.30 lbs, and sample #4 required 0.80 lbs. Samples #3 and #4 were removed from the study in May 2014.

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 foul-release coatings tested prior to December 2012.

Partners 2014-MTA-8-1008 and 2014-MTA-8-1009 provided, respectively, one and four experimental formulations. These samples went into exposure in May 2014. There are no results to show at this time.

Automotive Silicone Gasket Materials

In May 2013, MERL decided to test automotive 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 different RTV silicone gasket materials were selected with varying mechanical and physical properties. Two of the six gasket materials prevented mussel attachment following 12 months of exposure: gasket material #1 and #2. The surfaces of the gaskets were very rough due to the high viscosity of the liquid applied gasket materials.

Reclamation Experimental Formulations

In 2012, MERL began formulating foul-release coatings to better understand how and why the mussels attached to traditional RTV silicone, while the foul-release technologies prevented mussel attachment. The goal was to increase the strength of the silicones, while maintaining foul-release performance. The evaluation of these formulations is ongoing, and the current results are listed in the appendix in a separate table. In March 2014, MERL entered into a Cooperative Research and Development Agreement with an industrial partner with the intent of developing a durable foul-release system.

SUMMARY

- Silicone-based foul-release coatings continue to perform well in field testing at Parker Dam.
- Silicone Epoxy #7 and 2012-MTA-8-1003 #1 and #2 show promise as durable foul-release coatings that prevents mussel attachment or that are self-cleaning.
- All of the commercially available durable foul-release coatings evaluated prior to December 2012 failed to deter mussel attachment during long-term testing.
- The mechanism for mussel removal during waterjet cleaning involves severing the byssal threads for durable foul-release coatings as well as for epoxy, coal tar epoxy, and coal tar enamel.
- An ice phobic RTV Silicone coating allowed mussels to attach but was easily cleaned without leaving behind byssal threads.

- Two automotive RTV silicone gasket materials resist mussel attachment. There could be many more silicone caulks, gaskets, or membranes that resist mussels, but no others have yet been evaluated for mussel control.
- Reclamation has begun formulating foul-release coatings and has entered into a Cooperative Research and Development Agreement with an industrial partner with the intent of developing a durable foul-release coating.

REFERENCES

[1] Bureau of Reclamation. 2012. Coatings for Mussel Control — Three Years of Laboratory and Field Testing. Technical Memorandum No. MERL-2012-11. <https://www.usbr.gov/mussels/research/docs/20120821-MusselCoatings.pdf>

[2] NSF/ANSI Standard 61-2012, Drinking Water Systems Components.

[3] Research and Development Office. 2013. Resistance of Protective Coatings to High Pressure Water Jets for Invasive Mussel Removal. Bureau of Reclamation, Hydraulic Laboratory Technical Memorandum PAP-1074 <http://www.usbr.gov/pmts/hydraulics_lab/pubs/PAP/PAP-1074.pdf>

[4] SSPC SP1, Solvent Cleaning.

[5] SSPC SP10/NACE 2, Near white blast cleaning.

[6] ASTM A788, Specification for Steel Forging, General Requirements.

[7] AISI 304, Stainless steel

[8] ASTM Standard D 5618-94. 2011. Standard Test Method for Measurement of Barnacle Adhesion Strength in Shear. ASTM International, West Conshohocken, PA, 2010, DOI: 10.1520/D5618-94R11, www.astm.org.

[9] Kohl, J.G., and I.L. Singer. 1999. Pull-off behavior of epoxy bonded to silicone duplex coatings. *Progress in Organic Coatings* 36:15-20.

[10] Brady, R.F., Jr. 1999. Properties which influence marine fouling resistance in polymers containing silicon and fluorine. *Progress in Organic Coatings* 35:31-35.

[11] Brady, R.F., Jr., and I.L. Singer. 2000. Mechanical factors favoring release from fouling coatings. *Biofouling* 15:73-81.

[12] Brady, R.F., Jr. 2001. A fracture mechanical analysis of fouling release from nontoxic antifouling coatings. *Progress in Organic Coatings* 43:188-192.

[13] Berglin, M., N. Lonn, and P. Gatenholm. 2003. Coating modulus and barnacle bioadhesion. *Biofouling* 19(S):63-69.

[14] Clare, A.S., and N. Aldred. 2009. Chapter 3, Surface colonization by marine organism and its impact on antifouling research. In: Hellio, C., and D. Yebra. *Advances in Marine Antifouling Coatings and Technologies*. Woodhead Publishing, Oxford. pp. 46–79.

[15] Skaja, A.D. 2010. Testing coatings for zebra and quagga mussel control. *Journal of Protective Coatings and Linings* 27(7):57-65.

[16] Wikipedia. 2014. Polyglycolide. Accessed July 2014. <http://en.wikipedia.org/wiki/Polyglycolide>

Appendix

Complete Material Testing Log: Years 2008–2014

	Generic Name or Trade name	Code Name	Dates tested	Durable Yes/No	Max Force To Remove Mussels (lb)	Most Recent Blockage or Coverage (for plates)	Comments
1	100% Zn Metallizing	100% Zn Metallizing*	05-2008 to 12-2008	Yes	N/A 1st year	50%	Many mussels
2	2012-MTA-8-1003-1	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	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	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	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	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	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	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	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	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	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	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	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	2012-MTA-8-1005-5	12-2012 to 12-2013	Yes	0.58	100% Coverage (3”x6” Plate)	Fully fouled

	Generic Name or Trade name	Code Name	Dates tested	Durable Yes/No	Max Force To Remove Mussels (lb)	Most Recent Blockage or Coverage (for plates)	Comments
15	304 Stainless Steel	304 Stainless Steel*	06-2010 to 05-2012	Yes	1.75	100%	Fully fouled
16	3M Lexzar V Maxx	Polyurea #2*	11-2011 to 12-2012	Yes	1.60	86%	Fully fouled
17	85-15 Zn Al Metallizing	85-15 Zn Al Metallizing*	05-2008 to 12-2008	Yes	N/A 1st year	75%	Fully fouled
18	90-10 copper nickel	90-10 copper nickel	08-2008 to 12-2008	Yes	N/A 1st year	100% Coverage (12" plate)	Fully fouled
19	Aquafast	Silane FR #1	08-2011 to 05-2012	Yes	0.95	N/A (3"x6" plate)	Moderate mussel fouling, algae present
20	Aquafast Experimental	Silane FR #2	08-2011 to 05-2012	Yes	0.83	N/A (3"x6" plate)	Moderate mussel fouling, algae present
21	Aqualastic	Polyurea #1*	05-2009 to 1-2010	Yes	0.32	67%	Many mussels
22	AS&M Aerokret 12XS	Silicone FR#15	12-2012 to 12-2013	Yes	0.28	86%	Fully fouled
23	AS&M Aerokret 21XS	Silicone FR#14	12-2012 to 12-2013	Yes	0.40	87%	Fully fouled
24	Battelle	Experimental FR	10-2009 to 11-2010	Yes	0.77	55% (12" plate)	Many mussels
25	Bayer	Polyurea hybrid*	11-2010 to 5-2012	Yes	0.28	100%	Fully fouled
26	Bioclean Black	Silicone FR #4	10-2009 to present	No	0.173	64%	No mussels, some algae, slime, and plants, self cleaning
27	Bioclean White	Silicone FR #5	10-2009 to present	No	0.00	N/A (3"x6" plate)	No mussels, self cleaning
28	Brass	Brass*	05-2008 to 11/2010	Yes	1.31	62% (12" plate)	An occasional mussel, some slime

	Generic Name or Trade name	Code Name	Dates tested	Durable Yes/No	Max Force To Remove Mussels (lb)	Most Recent Blockage or Coverage (for plates)	Comments
29	Bronze	Bronze*	05-2008 to 5/2014	Yes	1.37	18% (12” plate)	Moderate mussel colonization
30	Cathacoat 304	Zinc rich primer #2*	05-2008 to 12-2008	Yes	N/A 1st year	100%	Fully fouled
31	Cathacoat 304L	Zinc rich primer #3*	05-2008 to 12-2008	Yes	N/A 1st year	75%	Fully fouled
32	Cathacoat 313	Zinc rich primer #1*	05-2008 to 12-2008	Yes	N/A 1st year	100%	Fully fouled
33	Ceilcote 222	Vinyl Ester*	10-2009 to 11-2010	Yes	0.53	100%	Fully fouled
34	Coal tar enamel	Coal tar enamel	5-2011 to 5-2012	Yes	0.64	17.5% (12” plate)	Fully fouled
35	Copper	Copper*	05-2008 to 5/2014	Yes	1.41	5% (12” plate)	A few mussels, some slime
36	Curex	Aluminum ion Anti-microbial	12-2008 to 05-2009	Yes	N/A 1st year	10%	Few mussels, blistered and corrosion
37	Dap Black	Gasket Material #6	3-2013 to 12-2013	No	0.37	70%	Fully fouled
38	Du Slip	Silicone Polyurea #1	11-2011 to 12-2012	Yes	1.60	71%	Fully fouled
39	Duraplate 235	Polyamide Epoxy*	5-2010 to 5-2011	Yes	1.40	87%	Fully fouled
40	Durashield	Moly-based epoxy*	11-2011 to 12-2012	Yes	0.94	100%	Fully fouled
41	Duromar HPL-2221LSE	Silicone Epoxy #4*	11-2010 to 11-2011	Yes	1.07	39%	Many mussels, blistered
42	Duromar HPL-2510FR	Silicone Epoxy FR #3	11-2010 to 11-2011	Yes	0.76	41%	Many mussels

	Generic Name or Trade name	Code Name	Dates tested	Durable Yes/No	Max Force To Remove Mussels (lb)	Most Recent Blockage or Coverage (for plates)	Comments
43	ECTFE	ECTFE*	05-2009 to 1-2010	Yes	0.41	44%	Many mussels
44	E-Paint SN-1	Organic AF #3	05-2008 to 12-2008	No	N/A 1st year	25%	Many mussels
45	E-Paint Sunwave plus	Organic AF #1	05-2008 to 05-2009	Yes	N/A 1st year	25%	Many mussels
46	E-Paint ZO-HP	Organic AF #2	05-2008 to 12-2008	No	N/A 1st year	20%	Many mussels
47	ETFE	ETFE*	05-2009 to 1-2010	Yes	0.43	51%	Many mussels
48	FEP	FEP*	05-2009 to 1-2010	Yes	0.47	46%	Many mussels
49	Fuji (Black)	Silicone FR #2	05-2009 to present	No	0.00	9%	No mussels, some algae, slime, and plants. Self-cleaning
50	Fuji + Duraplate	Silicone FR #7	06-2010 to 11-2011	No	0.00	6%	No mussels. Self-cleaning
51	Fuji Fish Screen	Silicone FR #2 (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	Silicone FR#1 Oil Free	7-2012 to present	No	0.00	5%	No mussels self-cleaning
53	Fuji Sept 2010 Formulation	Silicone FR #9	03-2011 to present	No	0.00	18%	No mussels. Self-cleaning
54	Fuji Tie + Duraplate	Silicone FR #6	06-2010 to 11-2011	No	0.25	30%	Many mussels, some algae, slime, and plants
55	Fuji White	Silicone FR #1	08-2008 to present	No	0.00	3%	No mussels. Self-cleaning

	Generic Name or Trade name	Code Name	Dates tested	Durable Yes/No	Max Force To Remove Mussels (lb)	Most Recent Blockage or Coverage (for plates)	Comments
56	Galvanized Steel	Galvanized Steel*	05-2008 to 12-2008 and 5/2010 to 5/2012	Yes	1.463	79%	Fully fouled
57	Hanson	Silicone Polyurea #2	11-2011 to 12-2012	Yes	0.651	100%	Fully fouled
58	Hempel: Hempasil X3	Silicone FR #13	12-2012 to present	No	0.00	2%	No mussels, some algae self-cleaning
59	Hullspeed	Silicone Epoxy FR #6	11-2011 to 12-2012	Yes	0.69	54%	Many mussels present
60	International Paint: Intersleek 425	Silicone FR#12	12-2012 to present	No	0.00	3%	No mussels, some algae self-cleaning
61	Intersleek 970	Fluorinated Silicone FR	05-2008 to present	No	0.25	9%	Few mussels, mostly on damaged area. Self-cleaning
62	Jotun Sealion Repulse	Silicone FR #16	5-2013 to present	No	0.00	2%	No mussels, self-cleaning
63	Jotun Sealion Resilient	Silicone Epoxy FR #7	5-2013 to present	Yes	0.19	5%	Some mussels, algae, plants, slime, sponges. Potentially self-cleaning
64	Lumiflon	Fluorinated Polyurethane Arch*	10-2009 to 11-2010	Yes	1.74	100%	Fully fouled
65	Luminore	Copper metal AF	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	Epoxy*	08-2008 to 12-2008	Yes	N/A 1st year	50% (12” Plate)	Many mussels

	Generic Name or Trade name	Code Name	Dates tested	Durable Yes/No	Max Force To Remove Mussels (lb)	Most Recent Blockage or Coverage (for plates)	Comments
67	Nusil 9707	Silicone FR #11	5-2012 to present	No	0.46	7%	No mussels, self-cleaning
68	Nusil R 1082	RTV Silicone*	5-2013 to present	Yes	0.20	86%	Fully fouled, low release force
69	Nusil: 9706	Silicone FR #10	5 2012 to 12-2012	No	N/A (Coating delam)	0%	Coating delaminated from primer
70	Permadri	Asphaltic*	08-2008 to 12-2008	Yes	N/A 1st year	25%	Many mussels, blistered
71	Permatex Black	Gasket Material #5	5-2013 to 12-2013	No	2.24 (plow)	100% Coverage (3”x6” Plate)	Fully fouled
72	Permatex Blue	Gasket Material #4	5-2013 to 12-2013	No	2.35 (plow)	100% Coverage (3”x6” Plate)	Fully fouled
73	Permatex Clear	Gasket Material #1	5-2013 to present	No	0.00	0 Coverage (3”x6” Plate)	No mussels some algae, plants
74	Permatex Gray	Gasket Material #3	5-2013 to 12-2013	No	0.60 (plow)	100% Coverage (3”x6” Plate)	Fully fouled
75	Permatex Red	Gasket Material #2	5-2013 to present	No	0.00	20% Coverage (3”x6” Plate)	No mussels, some algae, plants
76	PFA	PFA*	05-2009 to 05-2010	Yes	0.20	48%	Many mussels
77	Phasecoat	Silicone FR #8	11-2010 to 11-2011	No	0	5%	Poor lab test performance
78	Plasite 4500S	100% solids epoxy*	05-2008 to 12-2008	Yes	N/A 1st year	66%	Fully fouled
79	Plasite 9145 TFE	TFE Epoxy*	10-2009 to 11-2010	Yes	0.61	100%	Fully fouled
80	Polyglycolic acid	PGA*	7-2012 to 12-2013	Yes	0	N/A 3x6 panel	Few mussels and algae

	Generic Name or Trade name	Code Name	Dates tested	Durable Yes/No	Max Force To Remove Mussels (lb)	Most Recent Blockage or Coverage (for plates)	Comments
81	Polyset	Inorganic zinc	5-2013 to 5/2014	Yes	1.08	86%	Fully fouled
82	PPG Sigmaglide 890	Silicone FR #3	10-2009 to present	No	0.552 (p)	40%	Mussels on damaged area. Self-cleaning
83	PVDF	PVDF*	05-2009 to 11-2009	Yes	0.41	25%	Many mussels
84	Rilsan	Fusion bonded nylon*	05-2009 to 11-2009	Yes	N/A 1st year	25%	Many mussels
85	Rylar #1	1K Polyurethane FR #1	05-2011 to 11-2012	Yes	0.70	100%	Many mussels, blistered
86	Rylar #2	1K Polyurethane FR #2	11-2011 to 12-2012	Yes	1.36	37%	Moderate mussel colonization
87	Seacoat Seaspeed V5/ Amercoat	Silicone Epoxy FR #1	10-2009 to 11-2011	Yes	0.56	92%	Fully fouled
88	Seacoat Seaspeed V5/ Amerlock	Silicone Epoxy FR #2	10-2009 to 05-2012	Yes	0.56	72%	Fully fouled
89	Sealife	Cuprous oxide AF	05-2008 to 12-2008	Yes	N/A 1st year	25%	Many mussels
90	SEI Chemical SHC-500	Fluorinated Polyurethane FR	10-2009 to 11-2010	Yes	0.73	97%	Fully fouled
91	Seicoat GPA 300	Silicone Anti-Graffiti #1*	5-2012 to 5-2013	No	0.21	85%	Fully fouled, low release force
92	Seicoat GPA 400	Silicone Anti-Graffiti #2*	12-2012 to 12-2013	Yes	0.34	93%	Fully fouled
93	Seicoat Nanoxirane	Silicone Anti-Graffiti #3*	12-2012 to 12-2013	Yes	0.52	95%	Fully fouled
94	Silver Bullet	Silver AM*	10-2009 to 11-2010	Yes	1.29	97%	Fully fouled, blistered

	Generic Name or Trade name	Code Name	Dates tested	Durable Yes/No	Max Force To Remove Mussels (lb)	Most Recent Blockage or Coverage (for plates)	Comments
95	Steel	Steel*	05-2008 to 12-2008	Yes	N/A 1st year	100%	Fully fouled
96	Targuard	Coal tar epoxy	5-2012 to 12-2012	Yes	1.71	60% Coverage (3”x6” Plate)	Many mussels
97	Tesla	Carbon Nanotube Epoxy	5-2013 to 12-2013	Yes	0.80	56%	Many mussels
98	Trunano	Nano AM*	05-2011 to 5-2012	Yes	0.939	86%	Many mussels
99	Wearlon	Silicone Epoxy FR #5	05-2008 to 12-2008	Yes	N/A 1st year	100%	Fully fouled

* Indicates product was not designed for preventing fouling.
N/A Indicates that coatings have not been tested long enough and no data are available.
1st year Means no quantitative data were collected due to initial qualitative approach.
AM Anti-microbial.
FR Foul-release.

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%