RECLAMATION

Managing Water in the West

Technical Memorandum No. MERL-2012-11

Coatings for Mussel Control — Three Years of Laboratory and Field Testing

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

March 2012

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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U.S. Department of the Interior
Bureau of Reclamation
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Coating for Mussel Control — Three Years of Laboratory and Field Testing

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Acronyms and Abbreviations

DIFT	Deionized Water Immersion Flow Test
ft	feet
ft^3/s	cubic feet per second
ft/sec	feet per second
JPCL	Journal of Protective Coatings and Linings
MERL	Materials Engineering and Research Laboratory
PVC	polyvinyl chloride
Reclamation	Bureau of Reclamation

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INTRODUCTION

Zebra mussels were first discovered in the United States in the 1980s in the Great Lakes. Then, in January 2007, Quagga mussels were found in Lake Mead (Hoover Dam). Since then, the mussels have spread downstream and have been discovered in the Colorado aqueduct as well as the Central Arizona Project. There have also been confirmed detections of Zebra and Quagga mussels in many other reservoirs in the western United States. Due to the warm climate of the southwest, mussels are able to reproduce at greater rates than in the Great Lakes Region and Upper Mississippi River Basin.

The mussels have the potential to disrupt water delivery and hydropower generation functions, as well as create long-term economic impacts. Mussels attach to underwater surfaces and can clog small-diameter piping (i.e., cooling water, HVAC, and domestic water piping), can reduce flow in larger diameter piping, and can clog fish screens, and impact intake structures.

Due to the potential impacts mussels have at Bureau of Reclamation (Reclamation) facilities, a coatings research project was started in 2008 to identify or develop solutions to mitigate problems caused by mussels. This report combines all the knowledge gained in the past three years of research on coatings for mussel control.

Most of the commercial products tested thus far have been marketed for fouling control in the shipping industry. However, the service environment at Reclamation facilities presents some unique challenges that must be considered when evaluating a fouling control coating. They include: highly variable water quality and numerous water borne substances that affect durability, including sediment loads, woody debris, vegetation, ice, and other debris. Therefore, these commercially available products had to be evaluated to determine if they could meet Reclamation's needs. Prior to this study, Reclamation did not have a strong need for coatings to address biofouling problems.

CONCLUSIONS

Over 50 coatings and metal alloys were evaluated. The coatings and alloys can be divided into six broad categories: conventional epoxies (no fouling control), foul release coatings, antifouling coatings, fluorinated powder coatings, metallic coatings, and metal alloys.

The conventional epoxies performed poorly; in general, those test samples were heavily fouled by mussels within 6 months. Four of the silicone foul release coatings remained mussel free after three years. The antifouling coatings performed well for up to 2 years. The copper metal filled polyester coating remained mussel free in static water (not flowing) after 3 years, but allowed mussel attachment in flowing water within 2 years. The fluorinated powder coatings were easier to clean than the conventional epoxies, but eventually (within 1 year) mussels did attach to these coatings. Zinc metalizing and galvanizing had poor performance in flowing water and fouled heavily within 6 months. The copper, bronze, and brass controls remained mussel free for three years, but their toxicity to other aquatic organisms makes them generally unfavorable for large-scale use at Reclamation facilities. ASTM A788 Steel and 304 stainless steel substrates fouled at an alarming rate - within 6 months the mussels completely blocked the 1-inch spacings of the grate [1].

The silicone foul release coatings are the most promising at deterring mussel attachment in both static and dynamic conditions. However, the silicones did exhibit fouling by bryozoans and algae, which provides a location for the mussels to eventually attach. The algae and bryozoans can be cleaned with minimal force to remove the fouling. Unfortunately, the majority of these coatings are soft and not very abrasion or gouge resistant. Nevertheless, for conditions that do not expose structures to heavy debris impacts, these coatings may perform well. Surprisingly, although they are soft, the 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 abrasion-resistant ceramic epoxies.

Future research is needed to further identify and evaluate new commercially available foul release technologies that will hopefully exhibit desirable abrasion and gouge resistance properties while maintaining foul release performance. As technology advances, there may eventually be a durable foul release coating that prevents mussel attachment. Additional research is also needed to determine the critical flow rates required for self cleaning of the durable foul release, fluorinated powder coatings, and the elastomeric coatings.

Field Test Site and Testing Conditions

Parker Dam was selected as the field test site to evaluate coatings in static (non-flowing) and dynamic (flowing) exposure conditions (shown in figure 1). 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 static exposure and were tied off by a nylon rope and lowered into the water to approximately 50 feet (ft) depth near the face of the dam. For the dynamic conditions, one 18-inch by 24-inch coated floor grate with 1-inch

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

spacings was tied off with two nylon ropes to prevent twisting and lowered to a depth of 40 ft below the water surface (about elevation 410 ft). The samples were hung downstream from the forebay trashrack structure.

The coated plates were 12 inches by 12 inches by 3/16 inches thick. The plates were prepared according to SSPC SP1 solvent cleaning and abrasive blast cleaning to a SSPC SP10/ NACE 2 near white metal blast with a 3.0 mil surface profile [2, 3]. All coatings were applied in accordance with the coating manufacturer's recommendations and in some cases samples were shipped to the coating manufacture for application. Figure 2 shows a set of coated plates being lowered into the water. The 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.

Several sets of controls were used, including epoxy coated steel, and uncoated carbon steel and stainless steel. ASTM A788 steel and 304 stainless steel were used to determine fouling rates for uncoated substrates as shown in figure 4 [1].

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.

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

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 feet per second (ft/s).

Measurements were obtained near the coated grate locations at flow rates of 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 (22,000ft^3/sec). 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 5 shows measured velocities during the lowest flow rate of 4,700 ft^3/s, figure 6 shows velocities at 9,800 ft^3/s, and figure 7 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.

Temperature

Temperature data were recorded on several test substrates from October 20, 2009, through October 2010, at 15-minute intervals. Figure 8 shows temperature data at elevation 410 ft, 40 ft below the water surface. Quagga mussels are capable of reproducing as low as 48^{o}F. Temperature data shows that at this facility the water temperatures would allow the quagga mussels to reproduce year round.

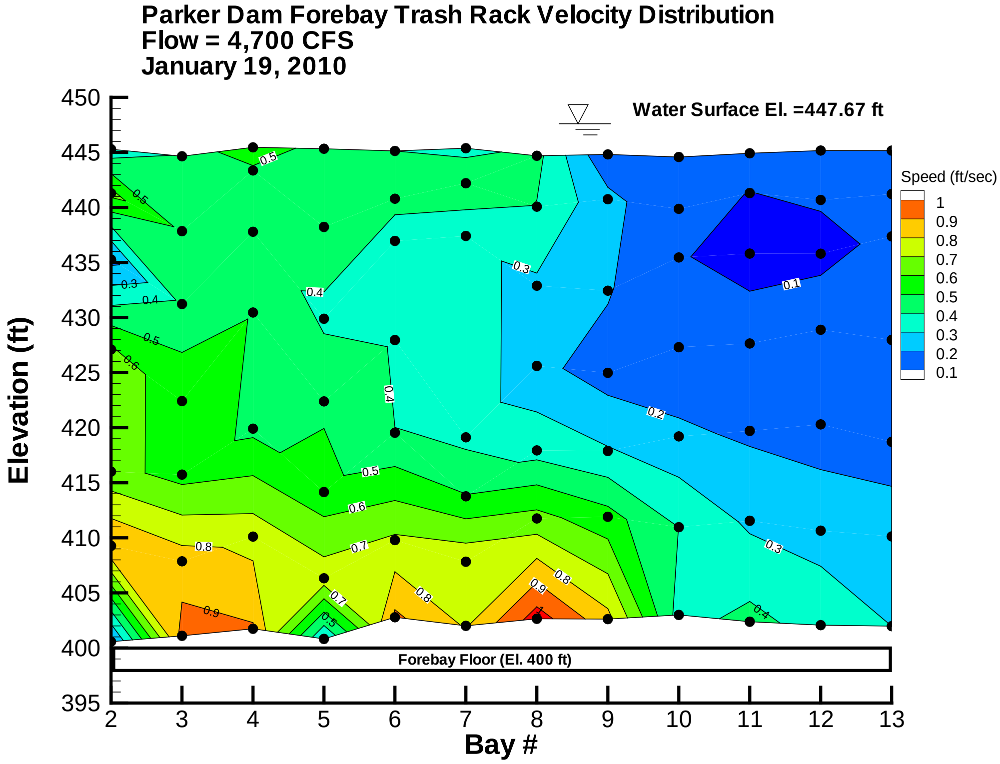

Figure 5.—Isovel plot of the velocity magnitudes passing through trashrack bays 2 to 13. The test grates were located near elevation 410 ft.

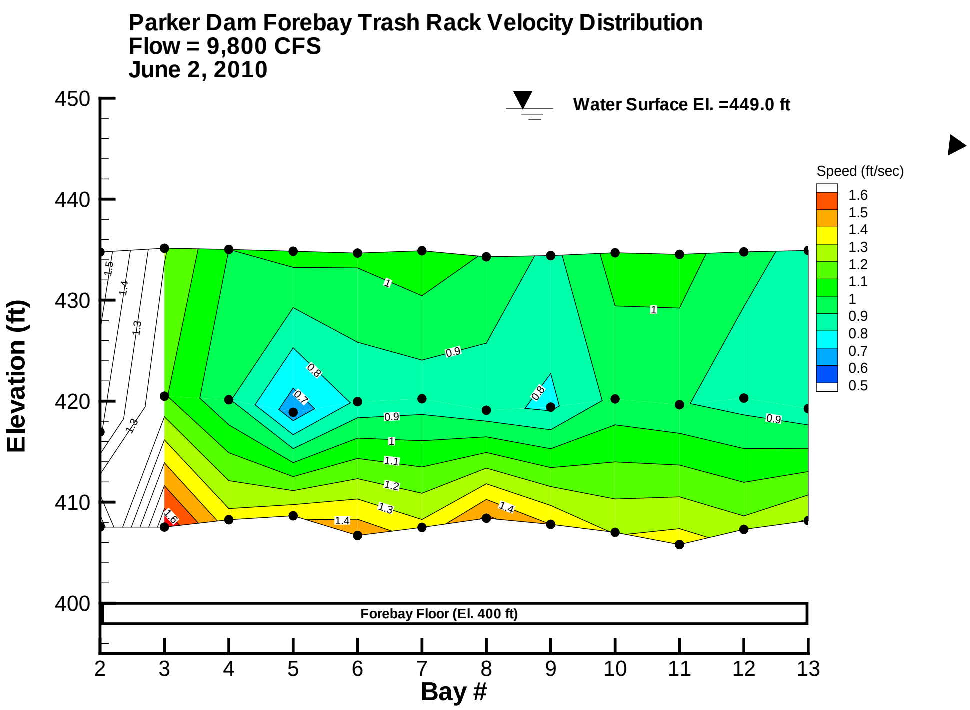

Figure 6.—Isovel plot of the velocity magnitude passing through trashrack bays 2 to 13. Units 3 and 4 were discharging 9,800 ft^3/s during the measurements.

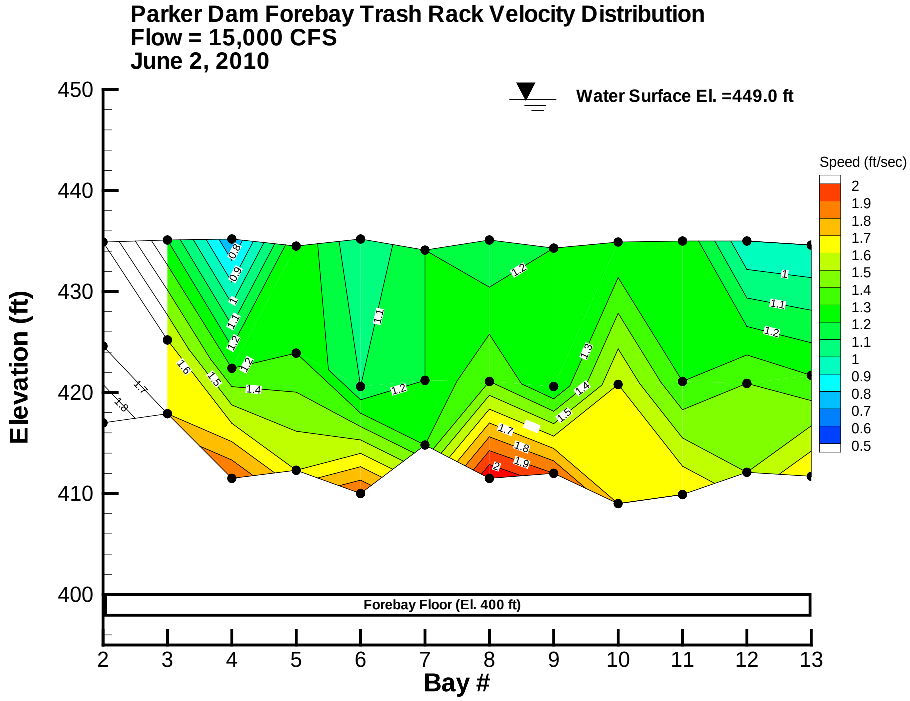

Figure 7.—Isovel plot of the velocity magnitude passing through trashrack bays 2 to 13. Units 1, 3, and 4 were discharging 15,000 ft^3/s during the measurements.

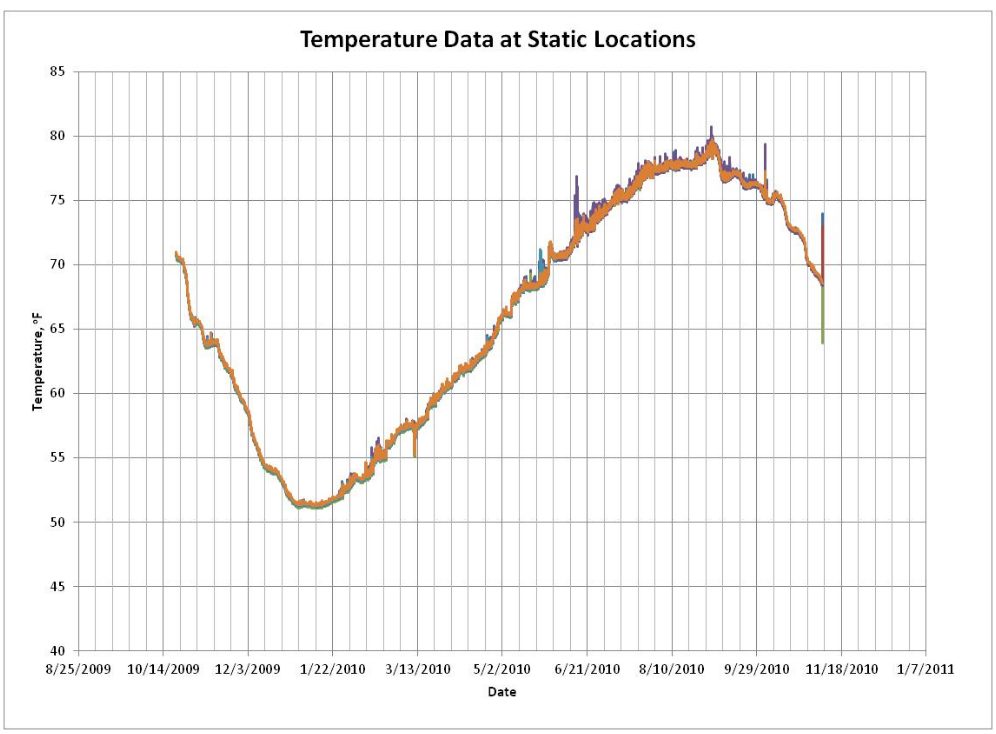

Figure 8.—Temperature data at elevation 410 ft, 30–40 ft below the water surface.

Veliger Sampling

Veliger sampling was conducted to determine when the mussels were spawning. Plankton tow net sampling procedures where used to sample veligers. The plankton tow net samples have been collected monthly by Parker Dam staff. The standard plankton tow procedure is used by the Technical Service Center's Environmental Sciences Laboratory. The volume water was calculated based on the net diameter and the length of the tow. The veliger samples were shipped to the Technical Service Center's Environmental Sciences Laboratory for quantitative analysis. Figure 9 shows the average number of veligers per liter of water. There is significant variability in the data due to limited sampling and non-uniform spatial distribution of veligers.

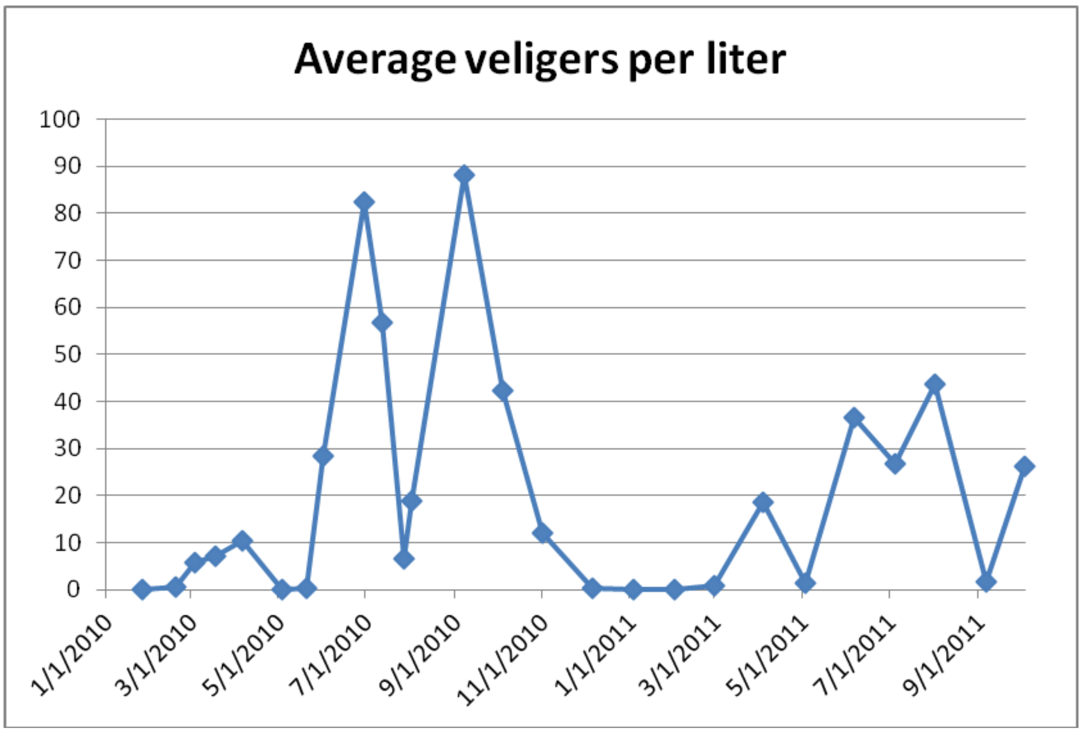

Figure 9.—Average number of veligers per liter of water from January 2010 through October 2011.

Results of the veliger sampling program indicate that the majority of mussel reproduction appears to occur in the warmer months between March and November. Comparing the veliger counts to water temperatures shows the mussels appear to have greater reproduction rates when water temperatures are above 58 ^{o}F.

EXPERIMENTAL PROCEDURES

The first year of testing was setup to be a qualitative testing program designed to determine whether the mussels attach to various coated surfaces. However, since the focus of the research changed in the second and third year to evaluating foul release coatings, the testing procedures changed. A more quantitative approach was needed to determine coating performance. We needed to determine the adhesion strength of mussels to various substrates and we needed to quantify the percent blockage on the grates or percent coverage on the plates. In addition, to confirm the presence of mussels, in November 2009, 2-inch by 6-inch stainless steel controls were attached to all samples.

New Measurements

Force Measurements

Mussel attachment strength was determined using a handheld force gage (Shimpo Model FGV-5XY, maximum capacity of 5 pounds). The procedure is modeled after ASTM D 5618-94, which is used to determine the attachment strength of Barnacles [4]. The major difference was that no attempt was made to measure the attachment area due to the difficulties in performing such a measurement with quagga mussels. It was impractical to measure the number of byssus that is attached to the surface in the field. Therefore, measurements are absolute forces and cannot be quantified in terms of stress since the bond area is unknown.

Mussels can attach on top of one another 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 is much greater than to remove one mussel. To get a more reproducible result, single mussels between 3/8- and 5/8-inch-lengths were targeted to measure the force. It was decided to take the maximum force rather than an average force 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.

Image Analysis

Quantitative image analysis was used to calculate the percent blockage on the grates and the percent coverage on the static plates. The percent of flow blockage for the grates was measured for all the coatings in the second and third year and were only estimated for the first year testing. This method measured all biofouling, which included algae, slime, bryozoans, and mussels, even though some coatings prevent mussel attachment. To obtain this information, the photos were evaluated using the graphics program IMAGEJ. A cropped image of each grate was selected for the analysis. A series of 20 random measurements were taken over the middle third of the image. A pixel count was then taken horizontally to measure the inner and outer spacing of the grate as shown in figure 10.

Figure 10.—Schematic for percent blockage calculation.

A percent blockage was calculated according to Equation 1.

Equation 1: $\%Blockage = \frac{L_1 - L_2}{L_1}$

The 20 data points were averaged and the blockage figure was corrected for the metal and coating thickness to allow for a direct comparison between substrates.

RESULTS AND DISCUSSION

Field Testing

Figure 11 shows the maximum force to remove individual mussels from the coated surfaces. The force gauge instrument was very sensitive, but all readings below 0.02 pound were assigned a zero force due to increased possibility for human error. Figures 12 and 13 show blockage after 1 and 2 years, respectively.

Silicone and Fluorinated Silicone Foul Release Coatings

The silicone foul release coatings (silicone FR #1 through #9) and fluorinated silicone FR fouled up to 30 percent, but this was primarily due to the

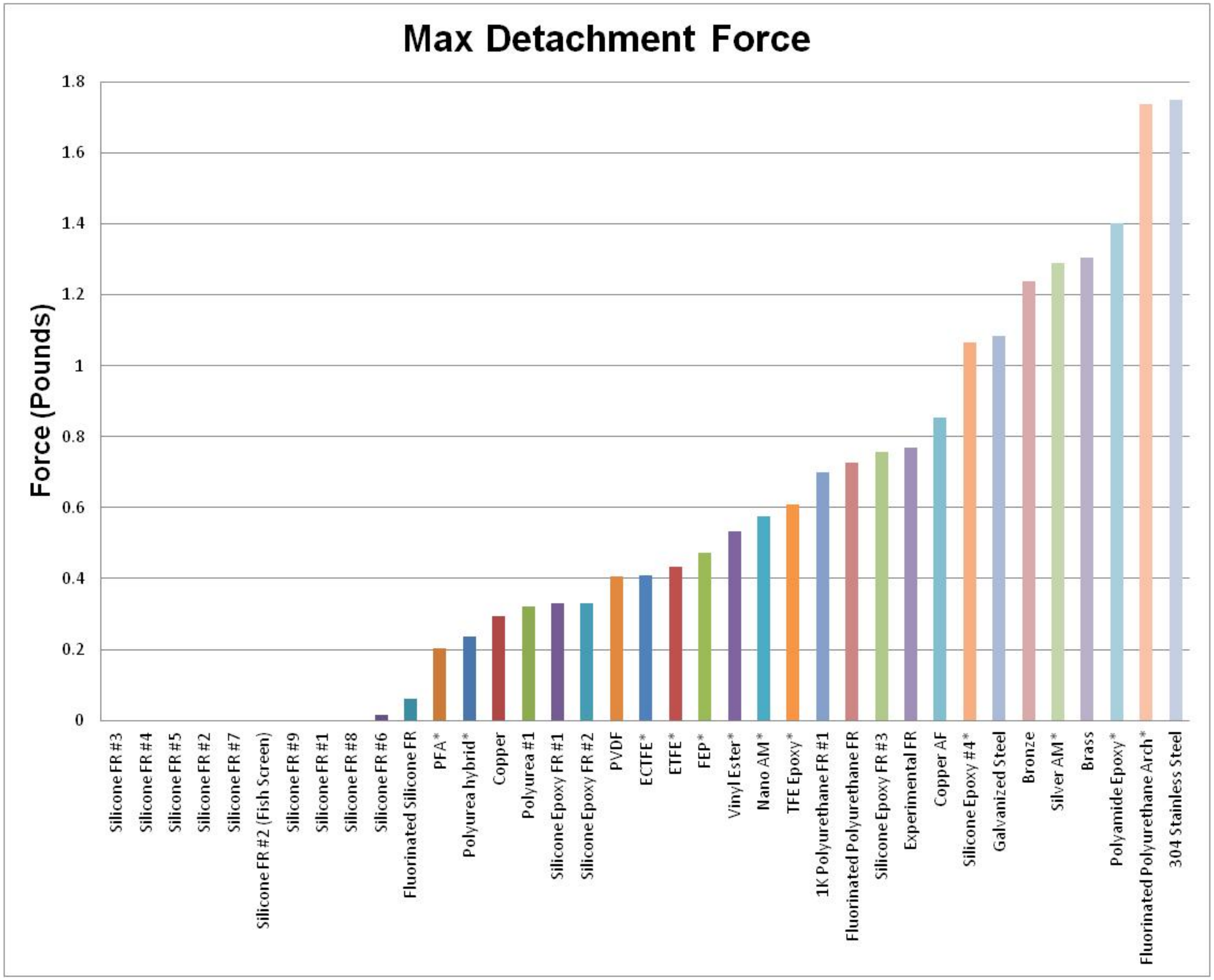

Figure 11.—Maximum attachment force on coated test plates suspended in static water. The symbol * means that the coating is not marketed specifically for fouling control.

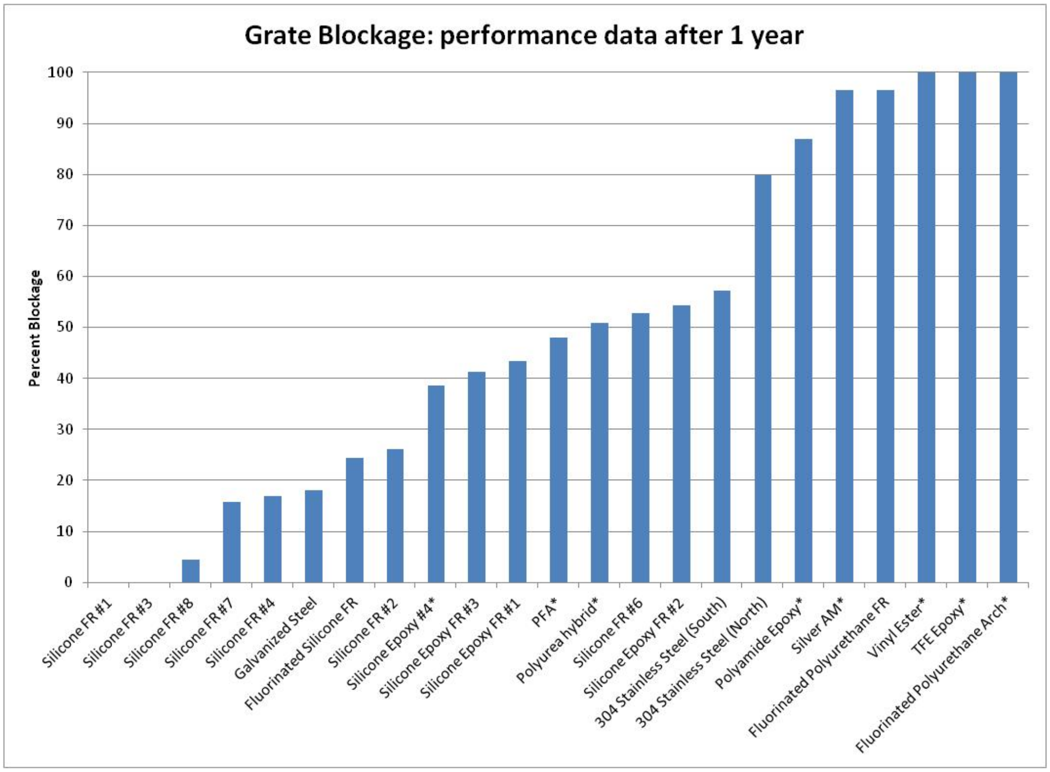

Figure 12.—Performance data for grates after 1 year of exposure.

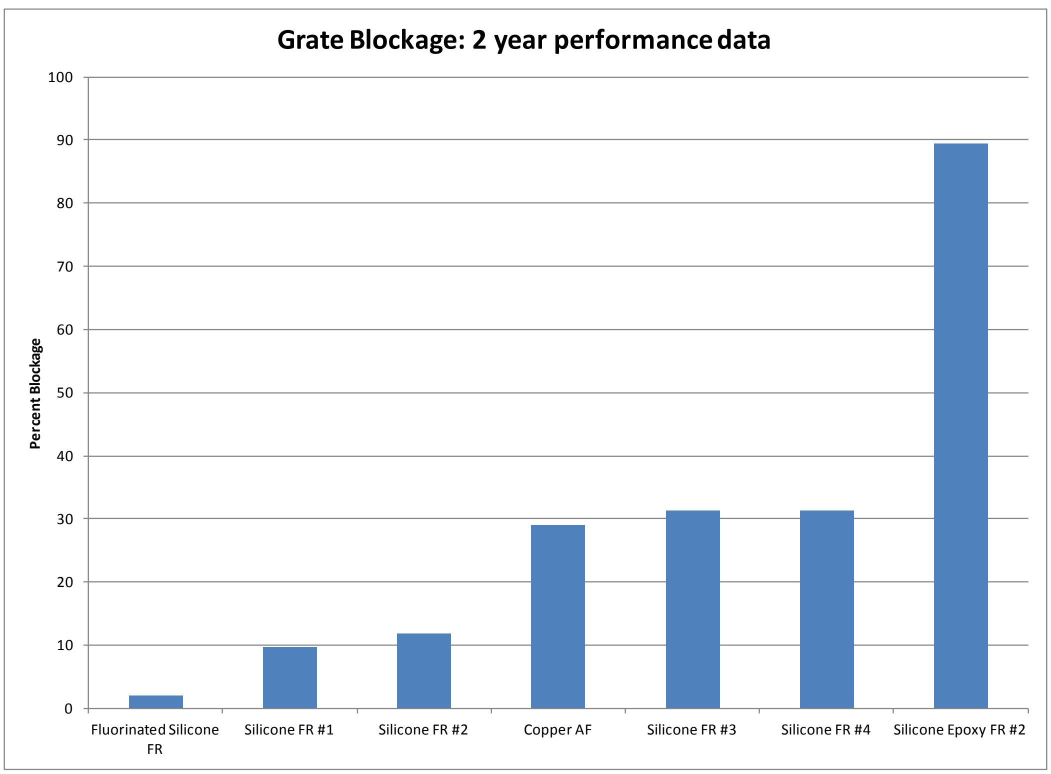

Figure 13.—Performance data for grates after 2 years of exposure.

accumulation of algae, slime, and bryozoans. Quagga mussels do not attach to the silicone surfaces. For some foul release coatings, there was a decrease in percent blockage of the grate from season to season as seen in figure 14. The 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 off the surface. Another possible explanation 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 which subjects the fouling to larger shear forces. During fall inspections, there was significantly less fouling on the silicone and fluorinated silicone foul release coatings than during the spring inspections. The velocity range during the summer months (or when all units are operating) was between 1.8 and 2.4 ft/s. The sloughing off has only been documented with the silicone and fluorinated silicone foul release systems.

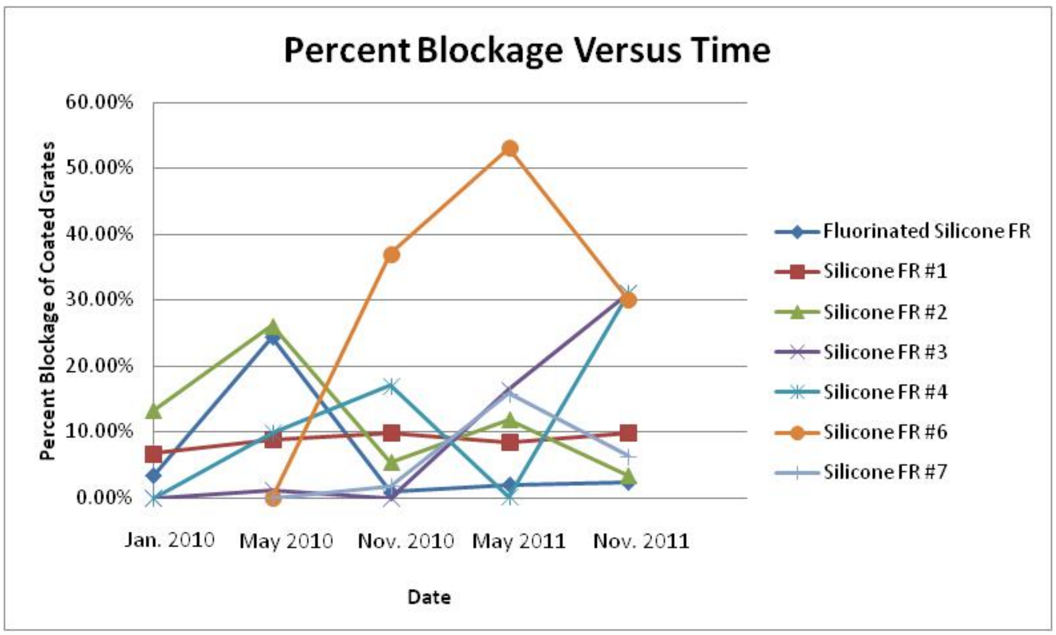

Figure 14.—Percent blockage of the silicone foul release coatings seasonal variation.

The silicone and fluorinated silicone foul release coatings have been successful thus far in preventing or minimizing fouling. The limitations will be when debris is present in the water that will rub, abrade, or gouge the coating. These coating systems should work well on infrastructure that is free of debris.

The silicone foul release coatings work based on two key physical properties, the low surface energy and the low elastic modulus. The low surface energy prevents the mussel adhesive to wet out to form a strong bond to the silicone surface effectively. The low modulus causes the mussel byssal plaque to fail in a peeling action rather than shear. The peeling mechanism requires less force than a shearing mechanism.

Silicone FR #8 was withdrawn from the study due to poor performance in the laboratory testing. The product was extremely slimy after application, and handling difficulties would be a significant issue.

Fluorinated Powder Coatings

Five different fluorinated powder coatings were evaluated between May 2009 and May 2010 (ECTFE, ETFE, FEP, PFA, and PVDF). All coatings eventually had mussel attachment. However, the force to remove the mussels was fairly low (around 0.4 pound of force to remove a mussel from four of the fluorinated powder coatings). PFA only required 0.2 pound of force to remove a mussel from the surface. After 1 year, the grates were 50 percent blocked. The PFA was pulled out of the water in May 2010 after 1 year of exposure. After going through the data and recognizing that some coatings are self cleaning, the PFA may need to be re-tested due to the low forces required to remove mussels. It might have been better to leave the sample in the test through the summer of 2010 because the mussels may have sloughed off with the higher flow rates. One limitation of the fluorinated powder coatings is that they require shop application and baked on at 500 ^{o}F in an industrial oven. Therefore, the item to be coated must fit in an industrial oven. These coating systems are being considered for future use with cleaning equipment. Most fish screen and trashrack sections should fit into an industrial-sized oven.

Self Cleaning Characteristics

The silicone FR #6 is actually a tie coat of one of the silicone foul release coatings and does not release the fouling as easily as the silicones. Figure 11 shows that the mussels barely attach to the surface of the tie coat (silicone FR#6 requiring only 0.02 pound of force to remove a mussel). This was the lowest measureable force for any of the coatings tested that actually allowed the mussels to attach to the surface. This coating system was selected to demonstrate the self-cleaning process. Silicone FR #6 fouled up to approximately 25 percent from May 2010 to November 2010 as shown in figures 15 and 16. Between November 2010 and May 2011, Silicone FR #6 fouled up to 50 percent as shown in figure 17. Sometime between May 2011 and November 2011, the mussels sloughed off and the November inspection showed the grate to only be 17 percent blocked as shown in figure 18. There appears to be a critical flow rate or drag force when the fouling sloughs off. It is well known that the critical flow rate for mussels to attach to any surfaces is 4.9 ft/sec [5]. Therefore, it can be assumed that there are different critical flow rates for fouling to be released from the various types of foul release coatings. We believe that the force to remove mussels is dependent

Figure 15.—Silicone FR #6 on the right and Silicone FR #7 on the left prior to exposure (May 2010).

Figure 16.—Silicone FR #6 on the right and Silicone FR #7 on the left after 6 months in dynamic exposure (November 2010).

Figure 17.—Silicone FR #6 on the right and Silicone FR #7 on the left after 1 year in dynamic exposure (May 2011).

Figure 18.—Silicone FR #6 on the right and Silicone FR #7 on the left after 18 months in dynamic exposure (November 2011).

upon the flow rate and/or drag forces. Either the fouling needs to build up to a certain thickness or the flow rates need to be increased in order to remove the fouling. Silicone FR #6 and FR #7 were used in a waterjetting study in December 2011 and test panels were very easily cleaned.

Durable Foul Release Coatings

So far, all of the durable foul release coatings evaluated allow mussel attachment. The coatings are easier to clean than a traditional epoxy coating. The self-cleaning phenomena has not been observed with the durable foul release coatings, but it may be because the durable foul release coatings require more than the 1 inch of growth in order for mussels to shear off the surface. Currently, a waterjet cleaning test is being conducted at Reclamation's Technical Service Center to determine the cleanability of the durable foul release coatings.

A water borne silicone epoxy foul release coating (silicone epoxy FR #5) was evaluated in 2008. The mussels attached to the surface, eventually blocking the grate 100 percent after 7 months of exposure. Force measurements were not done on this product.

Two solvent borne silicone epoxy foul release coatings (silicone epoxy FR #1 and #2) were evaluated in 2009. The attachment strengths were moderately low, with a 0.35 pound of force required to remove a single mussel. After 1 year of exposure, the grates were 50 percent blocked. These coating systems are being considered for future use with cleaning equipment.

A 100 percent solids silicone epoxy foul release coatings (silicone epoxy FR #3) was evaluated in 2010. The attachment strengths were moderately low, with a maximum of 0.76 pound of force required to remove a single mussel. After 1 year of exposure, the coated grate was 41 percent blocked. The silicone epoxy FR#3 coating system is being considered for future use with cleaning equipment.

A fluorinated polyurethane foul release coating (fluorinated polyurethane FR #1) was evaluated in 2009. In contrast to fluorinated polyurethane architectural coating, the product was advertised as a durable coating system optimized for foul release performance. After 1 year, the coated grate was 97 percent blocked. The force to remove mussels was 0.7 pound. This coating will not be considered for future use due to the high material cost, which was roughly three times more expensive as the silicone epoxy FR #1.

A durable one component polyurethane foul release coating was evaluated in 2011 (1K polyurethane FR #1). The results show the grate flowing to 18 percent blockage, and attachment strengths were moderately low, with a maximum of 0.7 pound of force required to remove a single mussel. The manufacturer reformulated their product, and currently, this product is being re-tested (1K polyurethane FR #2). The first version blistered severely in freshwater within 6 months.

Two durable silane foul release coatings were added to the study in August 2011 (silane FR #1 and #2). There has been no data collected at this time.

A durable silicone polyurea foul release coating was added to the study in November 2011 (silicone polyurea #1). There has been no data collected at this time.

Durable Low Coefficient of Friction Coatings

So far all of the durable low coefficient of friction coatings evaluated allow mussel attachment. Some of them are easier to clean than a traditional epoxy coating.

A PTFE-filled epoxy, vinyl ester, and a fluorinated polyurethane architectural coating system were identified as potential low friction alternatives to conventional epoxies and polyurethane coatings. All three systems were added to the test in October 2009. After 1 year of exposure, the grate samples were all 100 percent blocked. The vinyl ester and TFE epoxy showed the moderate bond strength of approximately 0.6 pound. The fluorinated polyurethane had an attachment force of 1.7 pounds. The vinyl ester and TFE epoxy will be considered as lower cost alternatives to the durable foul release coatings.

A 100 percent solids silicone epoxy low surface energy coating (silicone epoxy #4*) was evaluated in 2010. This product allowed mussel attachment to the surface and required 1 pound of force to remove a single mussel. The grate was 39 percent blocked after 1 year of exposure. The silicone epoxy #4 will not be considered for use due to severe blistering of the product.

Polyurea and silicone polyurea (polyurea #2* and silicone polyurea #2*) products that made the claim of not allowing ice to adhere to the coated surface were added to the study in November 2011. We decided to test these products for biofouling control. There are no test results at this time.

A molybdenum disulfide based epoxy coating (moly based epoxy*) was added to the study in November 2011. Molybdenum disulfide is used as a dry lubricant and has an extremely low coefficient of friction. We decided to test the product for biofouling control. This coating did not claim to resist mussel attachment, and there was no literature found saying it had been tested. There are no test results at this time.

Antifouling Paints

Antifouling paints contain biocides to prevent fouling. All of the antifouling paints evaluated had a short life of 1 to 2 years in flowing water. Their performance was better in static water. All antifouling coatings have been withdrawn due to the superior non-toxic silicone foul release coatings performance. Future antifouling coatings will only be evaluated if the manufacture can prove there are no environmental or ecological impacts, from biocides, on freshwater species.

A cuprous oxide based antifouling paint was evaluated in 2008. The mussels attached in flowing water but not in static immersion. The grate was about 25 percent blocked after 7 months of exposure. It is believed that the ablation rate was not matched for the freshwater conditions.

A copper metal antifouling paint was evaluated in 2008 to 2010. 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. It required 0.85 pound of force to remove a single mussel. The coated substrates in static water are still mussel free after 3 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 is causing the copper to leach at a faster rate than static conditions.

A peroxide antifouling paint (organic AF #1) was evaluated in 2008 to 2009. The mussels attached to the surface, eventually blocking about 25 percent of the grate after 1 year of exposure. Force measurements were not done on this product.

A zinc omadine antifouling paint (organic AF #2) was evaluated in 2008. The mussels attached to the surface, eventually blocking about 20 percent of the grate after 7 months of exposure. Force measurements were not done on this product.

A seanine 211 antifouling paint (organic AF #3) was evaluated in 2008. The mussels attached to the surface, eventually blocking about 25 percent of the grate after 7 months of exposure. Force measurements were not done on this product.

Antimicrobial Coatings

Three antimicrobial coatings were evaluated for biofouling control. All three systems did not prevent mussel attachment.

An aluminum ion antimicrobial coating (aluminum ion AM) was evaluated in 2008. The coating allowed mussels to attach. Force measurements were not performed on this product. At the time the coating was withdrawn, the grate was only 10 percent blocked. The product was withdrawn from the study due to corrosion and blistering of the product.

A silver ion antimicrobial coating (silver AM*) was evaluated in 2009. After 1 year, the coated grate was 97 percent blocked, and a force of 1.3 pounds was required to remove mussels. This coating did not provide any improvements over a traditional epoxy coating and will not be considered for future use.

A nanoparticle antimicrobial coating (nano AM*) was evaluated in 2011. The product allowed the mussels to attach and required 0.575 pound of force to remove an individual mussel. The coated grate was 42 percent blocked after 6 months of exposure. Currently, this product is still being evaluated and a final decision will be made after 1 year of exposure.

Elastomeric Coatings

So far all of the elastomeric coatings evaluated allow mussel attachment. They are easier to clean than a traditional epoxy coating.

A polyurea coating (polyurea #1*) was evaluated in 2009 for biofouling control. The polyurea #1 allowed the mussels to attach to the surface and required 0.32 pound of force to remove a single mussel. After 1 year in service, the grate was 67 percent blocked. The polyurea #1 may be considered as a low-cost alternative to the durable foul release coatings.

A 100 percent solids aliphatic polyurethane/polyurea hybrid (polyurea hybrid #1*) was evaluated for biofouling control in 2010. This product allowed the mussels to attach to the surface and required 0.23 pound of force to remove a single mussel. After 1 year in service, the grate was 51 percent blocked. The polyurea hybrid #1* may be considered as a low-cost alternative to the durable foul release coatings.

Metals and Metallic Coatings

The zinc metallic coatings allowed mussel attachment, which was different from reports from the U.S. Army Corps of Engineers. It is believed that performance may depend on water chemistry and that calcium levels in Lake Havasu may interfere with the performance of the zinc metal.

Galvanizing was evaluated twice, once in 2008 and again in 2011. Galvanizing allowed the mussels to attach. In 2011, galvanizing was re-tested to determine the amount of force required to remove a mussel, and it was found that 1 pound of force was required to remove a single mussel. The grate became 100 percent blocked at the end of 1 year of exposure.

Zinc metalizing and 85-15 zinc aluminum metalizing were evaluated in 2008 and allowed the mussels to attach. The grates were 50 and 75 percent blocked after 7 months of exposure, respectively. Force measurements were not performed on either metalized coating system.

Zinc Rich Primers

Three zinc rich primers were evaluated in 2008. All three zinc rich primers allowed the mussels to attach to the surface, allowing 75 to 100 percent blockage of the grate. Force measurements were not done on these three coatings.

Antifouling Metals

A 90-10 copper nickel alloy was an alloy that was supposed to prevent mussel fouling [10]. However, our results show that this particular alloy allows the mussels to attach. Within 4 months, the mussels completely covered the surface. Again, it could be the water chemistry that is affecting this alloy much like the galvanized steel. Force measurements were not conducted on this metal alloy.

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 does attach to the either of these surfaces, they adhere well. About 1.3 pounds of force was needed to remove a single mussel. The brass began having heavy mussel attachment in May 2010 after 2 years in immersion. The mussels do not adhere to copper nearly as well, requiring only 0.3 pound of force for removal. Copper was more effective than brass or bronze and remains essentially free of mussels after 3 years of testing.

Ferrous Metals

ASTM A788 steel and 304 stainless steel were used to verify the presence of mussels and to determine a fouling rate to be compared to coatings.[5] Both steel and stainless steel foul quickly; within a year the mussel completely block the grate so no water was flowing through the 1-inch openings. Over 1.7 pounds of force was needed to remove a single mussel.

Conventional Epoxy Coatings

Several different epoxy coatings were tested to get a baseline of attachment strengths of the mussels, including a polyamide epoxy, 100 percent solids epoxy, and a potable water epoxy. All epoxy coatings allowed the mussels to attach to the coated surface. The mussels attached to the surface with 1.4 pounds of force to remove an individual mussel. The epoxies also fouled at the same rate as ASTM A788 steel and stainless steel [1].

Laboratory Testing

Durability

The service environment that hydraulic equipment is subjected to at Reclamation facilities presents some unique challenges that warrant consideration; water quality is highly variable and rivers can carry high sediment loads, woody vegetation, ice, and other debris. Hence, durability has always been a concern when foul-release (FR) coatings are considered for use in Reclamation facilities due to their inherent soft nature. Furthermore, facility owners/managers are typically reluctant to remove intact and functioning coatings from equipment, so the ability to apply FR coatings over materials such as coal tar enamel (overcoating) is desirable.

It is standard practice for the Materials Engineering and Research Laboratory (MERL) to test coatings for corrosion protection, resistance to weathering, and cathodic disbondment using ASTM tests such as ASTM D 870 [7], ASTM D2794 [8], ASTM D5894 [9], ASTM D4587 [10], ASTM G8 [11]. The foul release coatings were evaluated against coatings currently specified by Reclamation since the foul release coatings require primers that are not currently approved as equivalent products. The ASTM standard testing results will not be discussed in this report.

While these ASTM tests are necessary to verify acceptable corrosion resistance performance, they are unlikely to provide an accurate prediction of service life for foul release coatings which are expected to fail due to mechanical damage. To address this issue, Reclamation has developed new (additional) test protocols to evaluate foul release coatings. The three additional tests are: a brush abrasion test, an erosion test, and a high flow water immersion test. The testing procedures are described below. The results from these tests are detailed in the following sections.

Non-ASTM Standard Testing Procedures

Brush Abrasion Test Procedure

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 x 6-inch panel was submerged in 10 ounces of filtered water in an acrylic tub and held in place by two C-clamps as shown in figure 19. 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

Figure 19.—Abrasion test setup.

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 wear tracks were created using three 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.

Erosion Testing Procedures

Reclamation's erosion test for coatings is based on ASTM C1138 [12], an erosion resistance test for concrete that involves circulating steel ball bearings in water. Three coated 3- x 6-inch samples were fastened to the base of an 11.5-inch internal diameter cylindrical tank as shown in figure 20. The tank was then filled with approximately 5 gallons of water and 900 grams of sieved sand (#16 - #20). A vertically oriented motor was connected to a helical paint stirring rod. Clearance between the rod and tank bottom was 3-3/8 inches. The tank was then sealed and the slurry was agitated vigorously at 1,140 rpm for 48 hours. The samples were then removed, dried, and weighed.

Assessing Sample Weight Loss

It was necessary to allow each freshly applied coating to reach equilibrium with the surrounding air. This was accomplished by using a convection oven set to

Figure 20.—Erosion test configuration.

50 ^{o}C to accelerate the curing process. Next, the coatings were hung on a drying rack in front of a large fan in order for the moisture content to reach equilibrium with the surrounding air. Equilibrium was deemed achieved when there was no significant weight change between two consecutive measurements 24 hours apart.

Once the coating cured, weight would continue to vary with temperature and relative humidity. Consequently, each set of samples was also assigned an identically coated control substrate. The weight of the control was recorded at the same time as the test sample weight was recorded. The final weight change for each test substrate was then adjusted by subtracting the weight change of the control. In this way, it was possible to adjust the readings for any changes in weight due to humidity variations in the laboratory.

After testing was completed, samples were also equilibrated using the fan/drying rack. This was required to make sure there was no affect from water absorption.

The amount of time required for equilibration was dependent on the amount of time the sample was submerged. For abrasion testing, samples were immersed for approximately 25 minutes and were allowed to dry overnight prior to performing mass measurements. Initial testing showed this drying time to be sufficient for achieving a stable sample weight. For the erosion testing, equilibrium was deemed when no significant weight change within two consecutive measurements space 24 hours. This time typically ranged from 7 to 10 days following the conclusion of the test.

Deionized Water Immersion Flow Test (DIFT) Procedures

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 1.

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

Table 1.—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/sec 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 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 25–30 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 four of the most promising coating systems, which are shown in table 2. Samples sizes were 1 x 6 inches in length on 1/8-inch thick steel. Two panels were coated with 1/16 – 3/32" of coal tar enamel by Lone Star Specialties in accordance with AWWA 203 Type II.[13] The coal tar enamel was prepared using a sweep blast SSPC-SP7 technique using a coal slag abrasive to create a 10 mil (approximate) profile. A third panel was prepared to SSPC SP5 white metal blasted steel with a 3 mil surface profile. The samples were coated with one to two coats of primer, tie coat(s) (if applicable), and a foul release top coat in such a manner as to leave approximately 1 centimeter of each coat exposed.

Table 2.—Systems tested for overcoating coal tar enamel

System	Existing substrate	Primer	Tie coat	Top coat
1	Coal tar enamel	97% solids epoxy	Silicone tie coat	Silicone FR #9
2	Coal tar enamel	100% solids epoxy	Silicone tie coat	Fluorinated-Silicone FR
3	Coal tar enamel	100% solids epoxy	N/A	Silicone Epoxy FR #3
4	Coal tar enamel	87% solids epoxy, 85% solids epoxy	Silicone tie coat	Silicone FR #3

The pump on the high flow immersion test was run each day for approximately 2 hours. The water temperature in the DIFT test ranged from 65 °F to 105 °F. On a few occasions, the pump was run for longer, and the water temperature was allowed to reach 118 °F.

Abrasion Resistance Test Results

The abrasion test produced visible scratching on nearly all of the samples. A commonly used polyamide epoxy was selected as a control to provide a baseline for comparison. On the polyamide epoxy as well as other durable samples (fluorinated polyurethane architectural coating*, and polyurea hybrid*), the scratches appeared to be fairly superficial on each of the test tracks. There was no significant difference in damage as additional weight was added to the brush. The weight losses were negligible for each of these samples (i.e., less than 10 milligrams).

The hard durable foul-release coatings resisted abrasion damage effectively and showed only slightly more physical damage and weight loss compared to the control samples. The durable foul release coatings tested included silicone epoxy FR #1 and #3 and the fluorinated polyurethane FR systems. There was a clear distinction between these coatings and softer silicone foul release coatings. The silicone foul release all experienced damage to a much higher degree with weight losses that ranged from 17 to 37 times greater than the best performing silicone epoxy.

In general, the harder coatings were far more durable than the softer coatings. However, one notable exception was the polyurethane-urea hybrid control sample, which was both soft and durable. The abrasion test results for the more durable coatings are given in figure 22a; results for silicone-based coatings are shown in figure 22b.

High Flow Immersion Test

All four 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 23. 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 is 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 is unlikely this problem is unique to foul release coating systems, but the extra coats that were required may aggravate the effect.

Erosion Resistance

The most notable physical change observed on the samples was a loss of gloss. It was difficult to gage the damage using visual inspection, so the samples were weighed to quantify the damage. Figure 24 shows the silicone foul release coatings exhibited excellent erosion resistance, comparable to an abrasion resistant epoxy. It outperformed the polyamide epoxy by more than 10 times less weight loss. One notable exception was Silicone FR #8, which experienced damage far greater than any other coating system. Silicone FR #8 was also unique in that the cured coated panel had a very oily feel in comparison to the other samples. Some silicone foul release coatings also outperformed a ceramic epoxy specifically designed to withstand erosion. However, the densities of the materials were significantly different, and the coating thickness loss was more important than the weight loss. Unfortunately, some of the coating densities were unknown, so the data could not be compared using the calculated thickness loss.

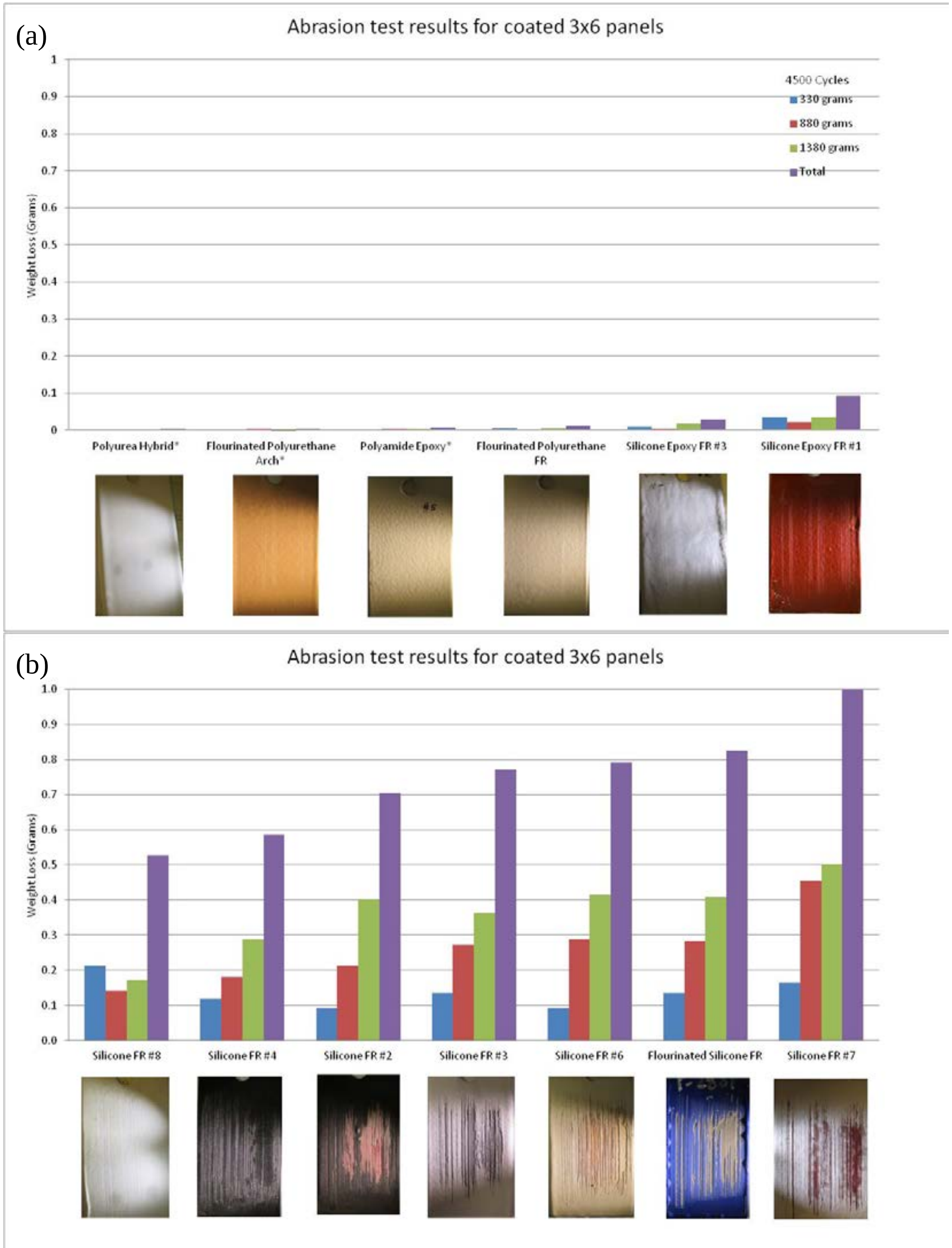

Figure 22.—Abrasion test results for (a) control samples and durable foul release coatings and (b) silicone foul release coatings.

Figure 23.—Failure of overcoated coal tar during a high flow test.

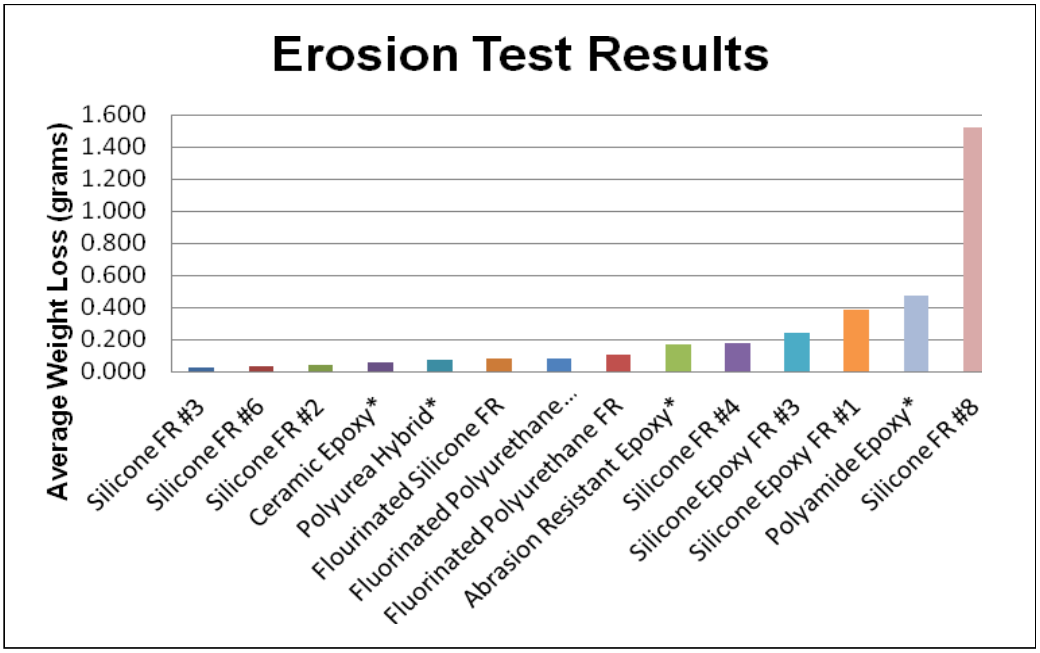

Figure 24.—Erosion test results for foul release coatings and controls. "*" denotes non-foul release systems.

General Discussion of Laboratory Program and Results

The test program used to evaluate durability of the foul-release coatings was developed by the Materials Engineering Research Laboratory at the Bureau of Reclamation. The tests were intended to simulate and accelerate the effects of a severe environment that a foul release coating may experience while in service. The brush abrasion test may represent cleaning of a trashrack/intake grating or contact from debris at the waterline of gates or trashracks.

The erosion test is intended to simulate the erosive action of water flow with entrained solid particulates. These results are most relevant to applications that see water flow such as intake structures, piping, turbines, and pumps.

A polyamide epoxy is a commonly used coating system for the immersion environment. The expected service life of an epoxy will depend on a variety of factors, but is estimated to be about 20 years. Ideally, a successful foul release coating would last as long as an epoxy or longer. Hence, it is desired that durability test results exceed that of the control for the application.

Several foul release coatings outperformed the epoxy controls in erosion testing, but abrasion resistance was much lower. Failure of one of these tests does not automatically eliminate a coating system from consideration, but it is important to recognize each product's limitations when developing performance specifications. Successful deployment of a silicone-based foul release coating will depend strongly on the service environment. Environments where silicone-based foul release coatings have contact with equipment or floating debris is likely should be avoided. Silicone epoxy coatings appear to be more resistant to this type of abrasion damage. None of the coating systems are recommended for application over coal tar enamel.

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Appendix

	Trade name	Generic description	Dates tested	Max force	Percent blockage	Comments
1	100% Zn Metallizing	100% Zn Metallizing*	05-2008 to 12-2008	1st year	**50%**	Many mussels
2	304 Stainless Steel	304 Stainless Steel*	06-2010 to 05-2011	1.748	**100%**	Many mussels
3	3M Lexzar V Maxx	Polyurea #2*	11-2011 to current	N/A no data	N/A	Just started test
4	85-15 Zn Al Metallizing	85-15 Zn Al Metallizing*	05-2008 to 12-2008	1st year	**75%**	Many mussels
5	90-10 copper nickel	90-10 copper nickel	08-2008 to 12-2008	1st year	**100%**	Many mussels
6	Aquafast	Silane FR #1	08-2011 to current	N/A no data	N/A	Just started test
7	Aquafast Experimental	Silane FR #2	08-2011 to current	N/A no data	N/A	Just started test
8	Aqualastic	Polyurea #1*	05-2009 to 11-2009	0.322	67%	Many mussels
9	Battelle	Experimental FR	10-2009 to 11-2010	0.768	55%	Many mussels
10	Bayer	Polyurea hybrid*	11-2010 to 11-2011	0.236	51%	Many mussels
11	Bioclean Black	Silicone FR #4	10-2009 to current	0	31%	No mussels, some algae, slime, and bryozoans
12	Bioclean White	Silicone FR #5	10-2009 to current	0	0%	No mussels
13	Brass	Brass*	05-2008 to current	1.306	62%	An occasional mussel, some slime
14	Bronze	Bronze*	05-2008 to current	1.239	0%	An occasional mussel, some slime

	Trade name	Generic description	Dates tested	Max force	Percent blockage	Comments
15	Cathacoat 304	Zinc rich primer #2*	05-2008 to 12-2008	1st year	100%	Many mussels
16	Cathacoat 304L	Zinc rich primer #3*	05-2008 to 12-2008	1st year	75%	Many mussels
17	Cathacoat 313	Zinc rich primer #1*	05-2008 to 12-2008	1st year	100%	Many mussels
18	Ceilcote 222	Vinyl Ester*	10-2009 to 11-2010	0.533	100%	Many mussels
19	Copper	Copper*	05-2008 to current	0.294	0%	An occasional mussel, some slime
20	Curex	Aluminum ion AM	11-2008 to 05-2009	1st year	10%	Few mussels, blistered and corrosion
21	Du Slip	Silicone Polyurea #1	11-2011 to current	N/A no data	N/A	Just started test
22	Duraplate 235	Polyamide Epoxy*	11-2010 to 11-2011	1.4	100%	Many mussels
23	Duraseal	Moly based epoxy*	11-2011 to current	N/A no data	N/A	Just started test
24	Duromar HPL-2221LSE	Silicone Epoxy #4*	11-2010 to 11-2011	1.066	39%	Many mussels, blistered
25	Duromar HPL-2510FR	Silicone Epoxy FR #3	11-2010 to 11-2011	0.758	41%	Many mussels
26	ECTFE	ECTFE*	05-2009 to 05-2010	0.408	44%	Many mussels

	Trade name	Generic description	Dates tested	Max force	Percent blockage	Comments
27	E-Paint SN-1	Organic AF #3	05-2008 to 12-2008	1st year	25%	Many mussels
28	E-Paint Sunwave plus	Organic AF #1	05-2008 to 05-2009	1st year	25%	Many mussels
29	E-Paint ZO-HP	Organic AF #2	05-2008 to 12-2008	1st year	20%	Many mussels
30	ETFE	ETFE*	05-2009 to 05-2010	0.432	51%	Many mussels
31	FEP	FEP*	05-2009 to 05-2010	0.472	45.50%	Many mussels
32	Fuji (Black)	Silicone FR #2	05-2009 to current	0	12%	No mussels, some algae, slime, and bryozoans
33	Fuji + Duraplate	Silicone FR #7	06-2010 to 11-2011	0	16%	No mussels, some algae, slime, and bryozoans
34	Fuji Fish Screen	Silicone FR #2 (Fish Screen)	05-2009 to current	0	16%	No mussels, some algae, slime, and bryozoans
35	Fuji Sept 2010 Formulation	Silicone FR #9	03-2011 to current	0	12%	No mussels, some algae, slime, and bryozoans
36	Fuji Tie + Duraplate	Silicone FR #6	06-2010 to 11-2011	0.017	53%	Few mussels, some algae, slime, and bryozoans
37	Fuji White	Silicone FR #1	08-2008 to current	0	10%	No mussels, some algae, slime, and bryozoans
38	Galvanized Steel	Galvanized Steel*	05-2008 to 12-2008	1.083	100%	Many mussels

	Trade name	Generic description	Dates tested	Max force	Percent blockage	Comments
39	Hanson	Silicone Polyurea #2	11-2011 to current	N/A no data	N/A	Just started test
40	Intersleek 970	Fluorinated Silicone FR	05-2008 to current	0.061	24%	Few mussels on grate, majority of surface mussel free, low force to remove
41	Lumiflon	Fluorinated Polyurethane Arch*	10-2009 to 11-2010	1.736	100%	Many mussels
42	Luminore	Copper metal AF	05-2008 to current	0.854	29%	Many mussels
43	Novacoat 2000 PW	Epoxy*	08-2008 to 12-2008	1st year	50%	Many mussels
44	Permadri	Asphaltic*	08-2008 to 12-2008	1st year	25%	Many mussels, blistered
45	PFA	PFA*	05-2009 to 05-2010	0.203	48%	Many mussels
46	Phasecoat	Silicone FR #8	11-2010 to 11-2011	0.05	6%	Poor lab test performance
47	Plasite 4500S	100% solids epoxy*	05-2008 to 12-2008	1st year	66%	Many mussels
48	Plasite 9145 TFE	TFE Epoxy*	10-2009 to 11-2010	0.322	100%	Many mussels
49	PPG Sigmaglide 890	Silicone FR #3	10-2009 to current	0	31%	No mussels, some algae, slime, and bryozoans

	Trade name	Generic description	Dates tested	Max force	Percent blockage	Comments
50	PVDF	PVDF*	05-2009 to 11-2009	0.407	25%	Many mussels
51	Rilsan	Fusion bonded nylon*	05-2009 to 11-2009	1st year	25%	Many mussels
52	Rylar #1	1K Polyurethane FR #1	05-2011 to 11-2011	0.698	18%	Many mussels, blistered
53	Rylar #2	1K Polyurethane FR #2	11-2011 to current	N/A no data	N/A	Just started test
54	Seacoat Seaspeed V5/ Amercoat	Silicone Epoxy FR #1	10-2009 to 11-2011	0.329	89%	Many mussels
55	Seacoat Seaspeed V5/ Amerlock	Silicone Epoxy FR #2	10-2009 to 05-2011	0.329	89%	Many mussels
56	Sealife	Cuprous oxide AF	05-2008 to 12-2008	1st year	25%	Many mussels
57	SEI Chemical SHC-500	Fluorinated Polyurethane FR	10-2009 to 11-2010	0.728	97%	Many mussels
58	Silver Bullet	Silver AM*	10-2009 to 11-2010	1.29	97%	Many mussels, blistered
59	Steel	Steel*	05-2008 to 12-2008	1st year	100%	Many mussels
60	Trunano	Nano AM*	05-2011 to 11-2011	0.575	42%	Many mussels
61	Wearlon	Silicone Epoxy FR #5	05-2008 to 12-2008	1st year	100%	Many mussels

	Trade name	Generic description	Dates tested	Max force	Percent blockage	Comments
62	Belzona Ceramic S metal	Ceramic Epoxy*				
63	Devgrip 238	Abrasion Resistant Epoxy*				

* indicates that it was not designed for preventing fouling.
N/A no data means that the coatings have not been in the water long enough.
1st year means no quantitative data were collected due to initial qualitative approach.