ELECTRIC POWER
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Cooling Water Intake Debris Management: Coatings for Biofouling Control

Technical Brief — *Debris Management Interest Group*

Coatings for Fouling Control — Biofouling and corrosion can pose significant threats to power plant cooling water intake structures (CWIS). In sufficient quantities, fouling organisms can block intake screening equipment (e.g., bar racks and traveling water screens) leading to reduced cooling water flow or, in extreme cases, structural failure of the screening equipment. Corrosion of submerged intake components can also degrade structural integrity of supporting members. Cooling water blockage and corrosion-related damage are concerns as they negatively affect facility reliability and performance, and result in a loss of revenue. This technical brief provides background on coatings to minimize fouling and corrosion at power plant CWIS. It includes information on the biology of fouling, control strategies, as well as lists of external resources such as key literature, websites, and contact information for technical experts on coatings.

Intake gate structure fouled with invasive mussels (image courtesy of U.S. Bureau of Reclamation).

ISSUE

Biofouling is the process by which microorganisms, plants, and animals accumulate on wet surfaces. This occurs on almost every surface that comes in contact with water, which causes many problems for industrial water users such as thermal and hydroelectric power plants. There are a wide range of aquatic organisms that contribute to biofouling problems, but common species include hydroids and bryozoans, mussels, barnacles, and algae. Two invasive species of freshwater mussels, quagga and zebra (*Dreissena bugensis* and *D. polymorpha*, respectively), have become species of special interest due to their ability to rapidly colonize on hard wetted surfaces and for their particular attraction to locations with constant low velocity flows; conditions common at surface water intakes. Water intakes inundated with such organisms experience large increases in head loss, resulting in increased operational costs and safety concerns. Organism colonization of thermal power plant intakes can coincide with and contribute to colonization of the entire circulating water system. Larger organisms or colony fragments can break off and contribute to the obstruction of condenser tubes and create other operational issues.

An additional concern at industrial water intakes is corrosion. Corrosion can be caused chemically, biologically, or simply mechanically, and may be exacerbated by biofouling. Chemical corrosion may be caused by reactions with the surrounding water or other corrosive chemicals in the water. Biological components may include increased corrosive properties found in water trapped between the structure and macro-fouling organisms (visible organisms), or reactions caused by the presence of microorganisms, which is known as microbiologically influenced corrosion (MIC). Additionally, equipment may be mechanically eroded by sand and silt. This erosion may contribute to corrosion by removing oxides or other corrosion residues, exposing uncorroded surfaces to additional corrosive action. This is frequently referred to as Flow Assisted Corrosion (FAC). Whatever the cause, this corrosion may contribute to large maintenance costs and potential safety concerns, as the structural integrity of the intake becomes compromised due to loss of material.

Fouling of CWISs has major implications for power plants that use surface water for cooling purposes such as:

- Flow restrictions/increased head loss
- Increased CWIS operations and maintenance (O&M) costs
- Corrosion
- Reduction in heat transfer capabilities due to reduced flow or downstream fouling

Coatings are widely used to minimize the impact of biofouling and corrosion on CWIS and other cooling water circulation components; this technical brief provides information on the nature of the problem and the various types of coatings available. Many of the coating discussed herein are intended for the dual purpose of preventing biofouling and corrosion. However, the main focus of this technical update is the prevention of biofouling with an emphasis on CWISs, not downstream components.

BIOFOULING

Biofouling of a submerged surface follows a general succession from smaller to larger organisms. This process consists of three main types of fouling: conditioning film, microfouling, and macrofouling.

The first adhesion of organic matter (proteins) to the wetted surface begins within hours. The proteins create a 'conditioning film' on the surface which allows for the growth of bacteria. The next fouling stage (microfouling) consists of accumulation of soft fouling organisms (e.g., algae, biofilm) which easily thrive on the coating of nutrients. About a day after the microfouling stage begins, bacteria and diatoms are significantly established on the fouled surface creating a biofilm. Macroalgae and protozoa follow about a week later, using the bacteria just as the bacteria used the conditioning film (Abarzua and Jakubowski 1995). After a short period of time, an initially clean surface may be completely inundated with macrofoulers, such as the mussels covering the steel grating sample seen in Figure 1 (Abarzua and Jakubowski 1995).

CORROSION

Corrosion of CWIS components can be attributed to chemical, mechanical, or microbiological influences. Corrosion can be general (an overall uniform thinning of material) or localized in particular areas.

Chemical corrosion is simply the breaking down of a surface due to the chemical reactions with the ambient water. General corrosion (uniform loss of material) of chemically reactive intake components is the most common type of chemical corrosion experienced. This is generally a very slow process and is likely to be more of a long-term concern rather than an acute one. The localized form of chemical corrosion tends to be more problematic, however, as it can create pits and crevices in intake components which may impact structural integrity.

Mechanical degradation involves the breaking down of surfaces due to physical interactions between the surface and the surrounding environment. A common form of mechanical degradation is erosion. Suspended particles in cooling or service water wear down the intake surfaces over time. Mechanical degradation may be generalized or local. Additional wear concerns may arise from CWIS that include mechanical cleaning, such as a trash rake. Mechanical cleaning raises particular durability concerns in coating selection.

Figure 1 – A completely fouled metal grate shows the extent to which biofouling can affect submerged structures (Image from Skaja et al. 2014).

Microbiologically influenced corrosion (MIC) refers to corrosion mediated by biofouling organisms (e.g., bacteria that constitute the biofilm). The term, "microbiologically influenced" refers to the ways that fouling bacteria can change the chemical composition of the surface of a material or alter the kinetics of chemical reactions to exacerbate the effects of chemical corrosion. An example of this is the bacteria *Gallionella* which causes pitting in carbon and stainless steels because of the high levels of iron and manganese excretion in their waste (EPRI 2012). The excretions of other bacteria can include sulfurous acid, nitrous acid, acetic acid and sulfuric acid. These acids will cause an area of low pH around the substrate and they generally cause substantial pitting in submerged steel. MIC is often a localized corrosion problem, as the bacteria tend to settle in cracks or pits on the surfaces of the components. In addition, the macrofouling colonies can provide a buffer against biocides and corrosion inhibitors, which can inhibit the prevention of MIC.

EXTENT AND OCCURRENCE

As described above, biofouling is a risk to all submerged surfaces. As a result, biofouling control efforts are part of nearly all industrial and recreational interactions mankind has with surface water. However, fouling in the marine environment has historically garnered the greatest attention, with most of the research effort expended to control fouling and corrosion on seafaring ships and seawater intake structures. More recently, however, freshwater mussels (e.g., zebra, quagga) have spread rapidly across the United States and have also been identified in Mexico (Wakida-Kusunoki et al. 2015). These invasive species have heightened the concern of fouling in freshwater environments. Components of these intake systems (e.g., pipes, screens) can be greatly affected and, in some cases, rendered useless from severe mussel fouling. The cleaning and maintenance of fouled systems can be costly, time consuming, and lead to partial or full shutdowns of important facilities (Rajagopal et al. 2012).

Corrosion is an age-old problem as widespread and common as biofouling. Surfaces that come in contact with water tend to corrode over time (e.g., metal oxidation, degradation of concrete). Seawater is much more of a concern for corrosion than fresh water, due to its higher concentration of chemically reactive constituents and ions (EPRI 2012).

CONTROL

Control of biofouling can be managed proactively, by discouraging attachment of fouling organisms, or reactively, by physically or chemically removing attached organisms. Due to the nature of biofouling and the operation of power plants, proactive (preventive) control is typically more effective, though a combined approach is often necessary. The focus of this brief is to describe the role coatings can play in proactive and combined approaches. Properly selected and applied coatings change the surface properties of submerged structures to reduce biofouling and corrosion. The ideal coating would prevent biofouling and corrosion, be simple to apply and reapply if necessary, remain durable against erosion and cleaning, and not release toxic materials into the environment.

Combating biofouling is a complex O&M challenge generally involving the use of potentially toxic compounds. There are numerous commercially available coatings that have been shown to be effective in various applications. Fouling control can be achieved chemically, biologically, and physically.

Chemical methods rely on the release of substances that are poisonous or irritating to the potential fouling organisms. These include coatings that release substances such as tributyltin (TBT). While TBT has been demonstrated to be effective, it has been banned in the U.S. since 2008 due to environmental concerns. Alternative copper-based coatings and biocide boosters have been developed to replace the TBT-based products; however, studies have shown that dissolved copper has an effect on the sensory organs of salmon, limiting its use in areas where salmon occur (Hecht et al. 2007). Another chemical control method employs an enzymatic reaction on the surface of the coating to create a film of hydrogen peroxide, which acts as a biocide. Both the enzyme and the hydrogen peroxide are considered environmentally friendly; however, this biocide may not be effective on all fouling organisms (Olsen et al. 2009). An alternative chemical control approach that does not include the use of coatings is chemical dosing or shocking. Chemical dosing is the continuous or intermittent release of biocides such as chlorine. If such a chemical release system is used, practitioners should consider the effect of these chemicals on and potential interactions with coatings that may also be in use in other parts of the system.

Biological control methods rely on a variety of enzymes or metabolites secreted by cells as substitutes for traditional biocides (Krug 2006, Cao et al. 2011). Because the organic secretions are biodegradable, they are more likely to be environmentally friendly (Kristensen et al. 2008).

Physical control methods include vibration, electrolysis, radiation, magnetic fields, or modification of the physical properties of surfaces. The effectiveness of vibration (e.g., acoustic technologies) for controlling fouling has been confirmed (Branscomb and Rittschof 1984). Hydroids, barnacles, and mussels can be inhibited to some extent by either external vibration sources or piezoelectric coatings (Miloud and Latour 1995 and as reviewed by Cao et al. 2011). However, the large power consumption of these methods is difficult to overcome. Other studies have evaluated magnetic fields, ultraviolet radiation, and radioactive coatings, but these methods are not practical for large-scale applications (Cao et al. 2011). The most common physical approach involves the modification of surface physical properties with coatings that provide a low surface energy, preventing a strong bond with the surface; or a low elastic modulus, which allows attached organisms to peel off with minimal force (Skaja et al. 2014). To the extent that standard O&M involves mechanical cleaning of wetted surfaces, the durability of a modified surface must be taken into consideration.

COATINGS

Antifouling Coatings

Antifouling coatings utilize a chemical approach to reduce fouling and are common in the power generation industry, but have a much longer history. Early antifouling coatings were present as copper sheeting attached to the hulls of wooden ships. A biocidal film formed on the copper when in contact with seawater. Modern coatings release chemicals (e.g.,

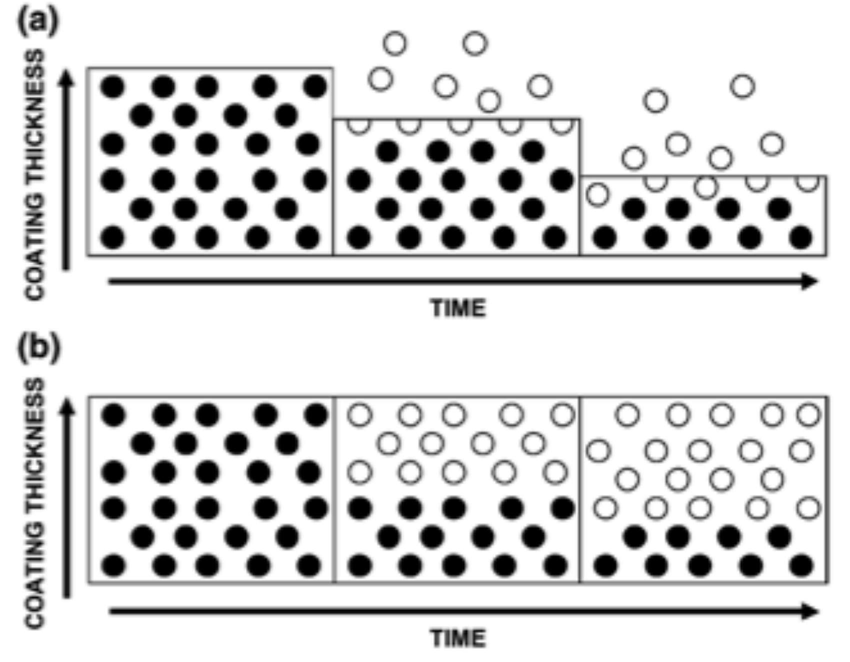

Figure 2 – Schematic of (a) soluble matrix biocide releasing coating and (b) insoluble biocide releasing coating. Black dots represent antifoulant loaded, white dots represent depleted antifoulant (Image from Chambers et al. 2006).

copper) in much the same way, to create a biocidal film. These matrices into which the biocide is incorporated can be either soluble or insoluble (Figure 2).

Cao et al. (2011) note that insoluble matrix antifouling paints have a polymer matrix (such as vinyl and epoxy) that will not erode in water. When the coating is immersed in seawater, the soluble toxic materials dissolve, which leaves a multiporous structure known as the leached layer. Seawater then penetrates deeper into the film and more toxic materials dissolve in the water. As Cao et al. (2011) note, the advantage of this kind of paint is that the structures are mechanically strong and stable to oxidation and photodegradation. Thus, the coatings can be made very thick to increase the content of toxic materials. However, at some stage, the leached layer will be so thick that water cannot penetrate any deeper, and the rate of release will fall under the minimum value required for antifouling (Yebra et al. 2004; Cao et al. 2011). Therefore, the lifespan of insoluble matrix antifouling paints can be as short as 12–18 months (Marson 1969 as also reviewed by Cao et al. 2011).

Cao et al (2011) reported that to lengthen the lifespan of antifouling coatings, soluble matrix antifouling coatings were developed. As implied by the name, both the toxic materials and matrix, which contains a great amount of resin, can dissolve in seawater. In this case, the leached layer can be much thinner and toxic materials deeper in the film can be more easily exposed to water, thereby lengthening the lifespan of the antifouling coating (Yebra et al. 2004 as also reviewed by Cao et al. 2011). The release rate increases exponentially as the water velocity increases. However, during the static conditions that favor settlement of fouling organisms, the pores of this coating can become blocked by insoluble salts which greatly reduces the release of biocides (Rascio et. al. 1990 as also reviewed by Cao et al. 2011). In addition, because of the resin's brittleness and instability to oxidation, its mechanical properties are inferior to those of insoluble matrix coatings (Cao et al 2011).

There are many commercially available epoxy-based antifouling coatings that claim to have increased longevity while maintaining biocidal effectiveness. However no long-term studies could be identified to support this claim.

Currently, the major copper compounds used in antifouling applications include metallic copper, cuprous thiocyanate, and cuprous oxide (Comber et. al. 2002, Omae 2003, Cao et al. 2011). Copper ions as Cu2+ play a major role in antifouling (Yebra et. al. 2004 as reviewed by Cao et al. 2011). Cao et al. (2011) note that compared with the broad-spectrum TBT antifouling coatings, copper-based coatings can only target specific fouling organisms. Biological indicators differ widely with respect to copper sensitivity and a general decreasing order of sensitivity is: microorganisms > invertebrates > fish > bivalves > macroalgae (Voulvoulis 1999 as reviewed by Cao et al. 2011). Therefore, some booster biocides that are highly toxic to macroalgae, barnacles, and bryozoans can be added to improve the antifouling proprieties. These biocides include Irgarol 1051 and Diuron (Omae 2003, Burma et. al. 2009, Cao et al. 2011), copper pyrithione, and isothiazolone (Shtykova et al. 2009). There are also many patented and commercially available antifouling coatings employing enzymes and hydrogen peroxide as biocides. Though many of these have shown promise in laboratory settings, no long-term test results could be identified.

The Fraunhofer Institute for Manufacturing and Advanced Materials Research has recently published their findings related to the adhesion of corrosion protection coating systems - organic coatings and duplex (spray metal and organic system) coatings. This three-year study evaluated special specimens exposed to an offshore environment to evaluate their protection performance. The results of the study indicated that all systems performed satisfactorily in terms of adhesion and that threshold pull-off strength limits were exceeded (Momber et. al. 2016).

Foul-Release Coatings

Due to concerns about the environmental and water quality impacts of biocidal antifouling coatings, some facilities utilize nontoxic forms of coatings. These coatings, referred to as foul-release coatings (FRC), are designed to create a smoother surface, making it harder for organisms to settle and colonize submerged surfaces. The two principal types of FRC are silicone- and fluoropolymer-based coatings (Chambers et al. 2006). FRCs are becoming increasingly popular, as they have been shown to be effective and have exhibited virtually no impact on the surrounding environment (Wells and Sytsma 2009). However, currently available products can be expensive, difficult to apply, and have limited durability.

Chen et al. (2008) evaluated a non-toxic, low surface energy coating prepared with modified acrylic resin and nano-SiO_2 demonstrating that the lower the surface energy and elastic modulus of the coatings, the less accumulation of biofouling. Holland et al. (2004) evaluated the adhesion strength of diatoms to silicone-based coatings. Results indicated that, in contrast to many larger macrofouling organisms, the single-celled diatoms adhered more strongly to the silicone-based coating than to glass. The authors indicate that removal of the diatomaceous slime on such coatings may have to be accomplished manually as even sea-going vessels operating at high speeds have not been able to release them.

Wells and Sytsma (2013) evaluated the costs and benefits of the Sher-Release/Duplex FRC (manufactured by FUJIFILM Smart Surfaces LLC) for controlling zebra and quagga mussels at the Dalles Dam on the Columbia River. The Sher-Release/Duplex coating was studied since it had been previously demonstrated to be effective for invasive mussels on the Columbia River, in a CA reservoir, at an Ontario Hydro facility, and other field experiments. The authors concluded that this coating was cost-prohibitive and not feasible since the coating has not yet been registered for use in freshwater facilities with salmonids.

Despite their effectiveness for preventing the proliferation of macrofouling organisms, practitioners should take into account their high cost as well as the convenience and cost of recoating.

Biomimetic Coatings

Biomimetics refers to the use of naturally-observed biological adaptations that confer a natural resistance to biofouling. The engineering of coatings that mimic these natural phenomena is a recent area of development in this field. Biomimetics has focused on both chemical and physical mechanisms that natural organisms use to provide protection against biofouling. Research on chemicals has focused on the production of secondary metabolites that deter fouling. Chambers et al. (2006) note that despite the research, no naturally-produced metabolites have become part of a commercially-available biofouling control technology. Research on physical phenomena has focused principally on the surface topographies and microtexture of marine organisms with a natural resistance to biofouling (e.g., placoid shark scales).

Composite Coatings

Fiber reinforced polymer (FRP), also known as fiber reinforced plastic, is a composite coating consisting of a polymer, such as epoxy or polyester, and a structure adding fiber, such as glass, carbon, or asbestos. These coatings are typically used for increased strength or resistance to chemical corrosion in applications ranging from civil infrastructure to aerospace (Masuelli 2013).

Some composite coatings are available that incorporate the benefits of various individual products into a single product. For example, Advanced FRP Systems offers multiple coating products that, when used together, can offer multiple benefits. Where MIC may have resulted in a corrosive loss of material (e.g., support for traveling water screens), such a composite material (comprised of a putty, a MIC-deterring epoxy layer, and a top foul-release layer) offers the potential to improve structural integrity, discourage the proliferation of MIC, and improve the foul-release capabilities of the surface.

Application of composite coatings involves grinding and smoothing of all sharp surfaces, solvent cleaning and heavy blasting of whole effective area, and filling all corners, welds, and imperfections before the application of the anti-corrosive or foul-release layers.

Composite systems contain very minimum amount of solvents (nearly 100% solids), and are thus more expensive and harder to apply. As a result these systems are likely to be more expensive than many standard coatings. However, the ability to repair instead of replace worn infrastructure must also be weighed when evaluating cost.

Thermal Spray Coating

Thermal spray coating is a process in which highly heated or melted materials are sprayed onto a surface. The coating materials are heated with a flame, electric plasma, or electric arc, and then accelerated toward the surface as molten particles by the expanding gases created in the heating process. The coating materials are available in a range of metals, plastics, ceramics, and alloys, which are fed into the system as a powder, wire, or rod. The system is typically used on metal objects, but the process transfers a relatively low amount of heat to the substrate allowing for many plastic and fiberglass applications.

Murakami and Shimada (2009; as cited in Fauchais and Vardelle 2012) evaluated the antifouling and anti-corrosion characteristics of various flame-sprayed powders on steel. The powders evaluated included aluminum-copper alloys, aluminum-copper blends, aluminum-zinc blends, and zinc. The best antifouling and anti-corrosion properties were seen with the aluminum-zinc blends with high zinc content and with the zinc coating.

Superhydrophobic Nano-coatings

Superhydrophobic materials possess a surface roughness so low that they resist all contact with water, so-much-so that even when submerged, a thin layer of air surrounds the material keeping it essentially dry. Nanotech coatings of such materials are now commercially available and are marketed for keeping surfaces clean, preventing corrosion, and preventing biofouling of boats. Some research has suggested that that these coating have promise for antifouling in short-term applications (Zhang 2005). Mahalakshmi et al. (2011) demonstrated that surface modification of titanium resulted in a superhydrophobic coating that significantly reduced microbial fouling (recall that the microbial layer is typically the first in the succession of biofouling). No full-scale evaluations could be identified that would indicate the long-term success of superhydrophobic nano-coatings.

Case Study: Coatings for Mussel Control - Results from Six Years of Field Testing (United States Bureau of Reclamation)

The Materials Engineering and Research Laboratory (MERL) conducted a study on behalf of U.S. Department of the Interior Bureau of Reclamation (USBR) to evaluate the effectiveness of over 100 materials and coatings for the prevention of biofouling of hydropower and other industrial water intakes by zebra and quagga mussels. The goal of the study was to find an effective material or coating that would also stand up to certain USBR durability and water quality standards. At the time of the 2014 technical memorandum (Skaja et al. 2014), the project was ongoing and in its sixth year of testing.

Figure 3 – Aerial view of the field study site, Parker Dam, CA (Image from Skaja et al. 2014).

The study was conducted at the USBR's Parker Dam on the Colorado River in California. This facility is afflicted with a large invasive mussel population known to reproduce nearly year-round. Each coating was applied to: 1) a 1 ft by 1 ft steel plate hung approximately 50 ft below the water surface in a relatively low flow location of the dam and 2) an 18 inch by 24 inch piece of steel floor grating with 1 inch spacing hung 40 ft below the water surface in a high flow location on the downstream side of the trash rack. Treatment and controls were placed in a similar fashion. Samples were left undisturbed for 6 month intervals, after which they were visually inspected and photographed for image analysis. If mussels were present, the peak shear force required to remove one mussel was recorded for comparison. If the sample was completely inundated by mussels, it was removed from testing. Durability testing was conducted by subjecting the samples to high pressure water jets and visually examining the surfaces.

The study began with many commercially available paints, coatings, and materials. Most were marketed as antifouling or foul-release, but other coatings such as anti-graffiti paints and silicone engine gasket material and metals such as stainless steel, copper, and copper alloys were also tested. With drinking water standards in mind, the focus was placed on FRCs, though many antifouling samples were tested. The selection of additional sample coatings and materials was driven by analysis of test results. Lackluster performance by the initially identified coatings resulted in a widening of the scope of the study to include coatings still in development. As part of the provisions made with the developers, the results of these tests were published with only a sample code, and very little material details. These samples were referred to as material transfer agreements (MTAs), the details of which were to be published at a later date, with the manufacturer's consent. The following are the categories of coatings and materials tested, as labeled in the report,

- Silicone and fluorinated silicone FRCs
- Durable FRCs
- Low coefficient-of-friction coatings
- Fluorinated powder coatings
- Anti-ice coatings
- Silicone anti-graffiti coating
- Molybdenum-disulfide containing coating
- Antifouling paints
- Copper alloys
- Zinc-rich primers
- Zinc metallic coatings
- Biodegradable polymer, and
- Material transfer agreements (MTAs).

Of the samples tested, the silicone FRCs showed the greatest promise. In some cases, FRC coated grates remained in good working order without any manual cleaning (Figure 4), indicating that the surface was essentially self-cleaning. Some of the FRCs resisted mussel growth for the duration of the six-year study.

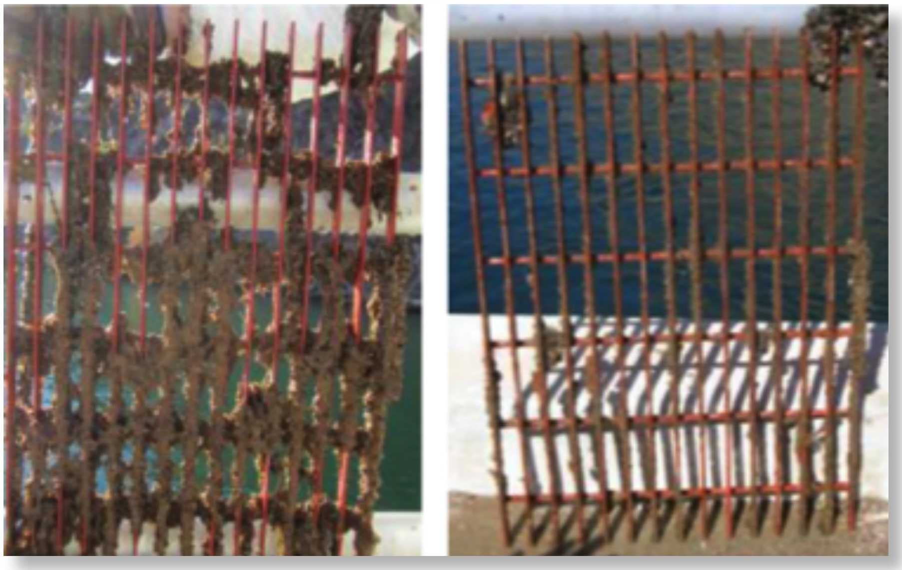

Figure 4 – FRC coated experimental grate fouled (left) and passively self-cleaned approximately 5 months later (right) (Image from Skaja et al. 2014).

However, as a group, these coatings lacked the durability to abrasion and gouging that is commonplace at CWIS with sediment and debris impacts. Silicone epoxy FRCs displayed acceptable durability and allowed only minimal growth which required less than 0.20 pounds of force for removal.

The copper sample also performed well in testing with nearly zero mussel growth on the copper after 6 years of testing. However, during this time, the copper sample eroded from 0.125 inch to 0.11 inch in thickness. This raises uncertainties regarding the service life of a copper structure as well as environmental concerns associated with rising dissolved copper levels in the water. Certain copper metal antifouling coatings performed well relative to durability and resistance to mussel growth for periods of up to two years. After this time, mussel growth began and the coatings started to blister. This lack of longevity and environmental concerns surrounding the release of copper into the waterbody eliminated these coatings from further consideration.

Two experimental MTAs displayed both durability and zero mussel growth after 18 months of testing. As stated previously, few details regarding the makeup of these coatings were provided and testing was ongoing as of the publication of the report.

At the time of the release of the report, MERL researchers had not identified a commercially available FRC that met all the performance, durability, and clean water standards set by the USBR. As a result, researchers were continuing to work with manufacturing partners in the development of a new coating that will meet their needs (Skaja et al. 2014).

CONTINUING RESEARCH

Despite the many effective and promising commercially available coatings, there appears to be no fail-safe solution for biofouling prevention at CWISs. An ideal coating would excel in the following areas:

- Ease of application/reapplication
- Durability
- Limited environmental impacts
- Limited impact on downstream CWC equipment
- Corrosion resistance, and
- Affordability.

FRCs and perhaps superhydrophobic coatings appear to have the most promise for effectively combining these properties and would benefit from further research. An antifouling coating that only releases toxins when and where organisms attempt to attach has also been discussed and may be worth additional research.

KEY RESOURCES

The following is intended as a starting point and resource for the reader to obtain more information on coatings used to prevent biofouling at CWISs. This section is not intended to be exhaustive and inclusion does not represent endorsement by EPRI.

Websites

Office of Naval Research Antifouling/ Fouling Release Coatings Program (http://www.onr.navy.mil/en/Science-Technology/Departments/Code-33/All-Programs/332-naval-materials/Antifouling-Fouling-Release-Coating.aspx)

U.S. Bureau of Reclamation Antifouling Coatings for Invasive Mussel Control (http://www.usbr.gov/research/projects/detail.cfm?id=7095)

Vendors

Advanced FRP Systems (http://www.advancedfrpsystems.com)
Ameron (http://www.ppgpmc.com)
Choguku MP (www.chugoku.com)
Fuji Film (http://www.fujifilmusa.com)
Hempel's MP (http://www.north-america.hempel.com)
International Paint/International Marine Coatings (http://www.international-marine.com/marinehome.aspx)
Jotun (http://www.jotun.com/ww/en/b2b/paintsandcoatings/products/SeaLion-Repulse.aspx)
Kansai (http://www.kansaipaint.net)

Experts

Below is a list of experts on coatings.

Cathy Karp
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REFERENCES

Abarzua, S. and S. Jakubowski. 1995. Biotechnological investigation for the prevention of biofouling. I. Biological and biochemical principles for the prevention of biofouling. *Marine Ecology Progress Series* 123: 301-312.

Branscomb, S.E. and D. Rittschof. 1984. An investigation of low frequency sound waves as a means of inhibiting barnacle settlement. *Journal of Experimental Marine Biology and Ecology* 79(2): 149–154.

Burma, A.G.J., S.B. Sjollema, W.H. van de Poll, H.J.C. Klamer, and J.F. Bakker. 2009. Impact of the antifouling agent Irgarol 1051 on marine phytoplankton species. *Journal of Sea Research* 61(3): 133-139.

Cao, S., J. Wang, H. Chen, and D. Chen. 2011. Progress of marine biofouling and antifouling technologies. *Chinese Science Bulletin* 56(7): 598-612.

Chambers, L.D., K.R. Stokes, F.C. Walsh, and R.J.K. Wood. 2006. Modern approaches to marine antifouling coatings. *Surface and Coatings Technology* 201: 3642-3652.

Chen M.L., Q. Yuan Yuan, Y. Li, and G. Hong. 2008. Structures and antifouling properties of low surface energy non-toxic antifouling coatings modified by nano-SiO_2 powder. *Science in China Ser B-Chem* 51(9): 848-852.

Comber, S.D.W., G. Franklin, M.J. Gardner, C.D. Watts, A.B.A. Boxall, and J. Howcroft. 2002. Partitioning of marine antifoulants in the marine environment. *Science of The Total Environment* 286: 61-71.

Electric Power Research Institute (EPRI). 2012. Open Cooling Water Chemistry Guidelines. EPRI, Palo Alto, CA. 1025318.

Fuchais, P. and A. Vardelle. 2012. Thermal sprayed coatings used against corrosion and corrosive wear. In: Advanced Plasm Spray Applications (ed) Jazi, H.S., InTech: http://www.intechopen.com/books/advanced-plasma-spray-applications

Hecht, S.A., D.H. Baldwin, C.A. Mebane, T. Hawkes, S.J. Gross, and N.L. Scholz. 2007. An overview of sensory effects on juvenile salmonids exposed to dissolved copper: Applying a benchmark concentration approach to evaluate sublethal neurobehavioral toxicity. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-83, 39 p.

Holland R., T.M. Dugdale, R. Wetherbess, A.B. Brennan, J.A. Finlay, J.A. Callow, and M.E. Callow. 2004. Adhesion and motility of fouling diatoms on a silicone elastomer. *Biofouling* 20(6): 323-329.

Kristensen, J.B., R.L. Meyer, B.S. Laursen, S. Shipovskov, F. Besenbacher, and C.H. Poulsen. 2008. Antifouling enzymes and the biochemistry of marine settlement. *Biotechnol Adv.* 26(5): 471-481.

Krug, P.J. 2006. Defense of benthic invertebrates against surface colonization by larvae: a chemical arms race. *Prog Mol Subcell Biol* 42: 1-53.

Mahalakshmi, P.V., S.C., Vanithakumari, J. Gopal, U. Kamachi Mudali, and B. Raj. 2011. Enhancing corrosion and biofouling resistance through superhydrophobic surface modification. *Current Science* 101(10): 1328-1336.

Marson, F. 1969. Antifouling paints. I. Theoretical approach to leaching of soluble pigments from insoluble paint vehicles. *Journal of Applied Chemistry* 19(4): 93-99.

Masuelli, M.A. 2013. Introduction of Fibre-Reinforced Polymers – Polymers and Composites: Concepts, Properties and Processes. In: Fier Reinforced Polymers – The Technology Applied for Concrete Repair (ed) Masuelli, M.A., InTech: http://www.intechopen.com/books/fiber-reinforced-polymers-the-technology-applied-for-concrete-repair

Miloud, R. and M. Latour. 1995. Application of mechanical waves induced by piezofilms to marine fouling preventions. *Journal of Intelligent Material Systems and Structures* 7(1): 33-43.

Momber, A. W., P. Plagemann, V. Stenzel. 2016. The adhesion of corrosion protection coating systems for offshore wind power constructions after three years under offshore exposure. International *Journal of Adhesion & Adhesives*. December 2, 2015.

Murukami, K. and M. Shimada. 2009. Development of thermal spray coatings with corrosion protection and antifouling properties. In: Thermal Spray 2009: Proceedings of the International Thermal Spray Conference (eds) Marple, B.R., M.M. Hyland, Y.-C. Lau, C.-J. Li, R.S. Lima, and G. Montavon. ASM Int. Materials. Park, OH, USA 1041-1044.

Olsen, S.M., S. Kiil, K. Dam-Johansen, L.T. Pedersen, and M.H. Hermann. 2009. Controlled release of environmentally friendly antifouling agents from marine coatings. Kgs. Lyngby, Denmark: Technical University of Denmark (DTU).

Omae, I. 2003. General aspects of tin-free antifouling paints. *Chem Rev.* 103(9): 3431–3448.

Rascio V., C. Giúdice, and B. Del Amo. 1990. High-build soluble matrix antifouling paints tested on raft and ship's bottom. *Progress in Organic Coatings* 18(4): 389–398.

Rajagopal, S., H.A. Jenner, and V.P. Venugopalan. 2012. Operational and Environmental Consequences of Large Industrial Cooling Water Systems. Springer Science and Business Media, New York, NY.

Shtykova, L, C. Fant, P. Handa, A. Larsson, K. Berntsson, H. Blanck, R. Simonsson, M. Nyden, and H.I. Harelind. 2009. Adsorption of antifouling booster biocides on metal oxide nanoparticles: Effect of different metal oxides and solvents. *Progress in Organic Coatings* 64(1): 20–26.

Skaja, A.D., D.S. Tordonato, B.J. Merten, and W.F. Kepler. 2014. Coatings for Mussel Control - Results from Six Years of Field Testing. U.S. Department of the Interior, Bureau of Reclamation. Technical Memorandum No. MERL-2014-64.

Voulvoulis, N., M.D. Scrimshaw, and J.N. Lester. 1999. Alternative antifouling biocides. *Applied Organometallic Chemistry* 13(3): 135–143.

Wakida-Kusunoki, A.T., F.T. Wakida, and J.M. De Leon-Sandoval. 2015. First record of quagga mussel *Dreissena rostriformis bugensis* (Andrusov, 1897) (Bivalvia, Dreissenidae) from Mexico. *BioInvasions Records* 4(1): 31–36.

Wells, S. and M. Sytsma. 2009. A Review of the Use of Coatings to Mitigate Biofouling in Freshwater. Prepared for the Bonneville Power Administration and the Pacific Marine Fisheries Commission.

Wells, S. and M. Sytsma. 2013. Estimating costs of using foul-release type coatings to mitigate *Dreissena* sp. Mussel macrofouling at a FCRPS facility. Prepared for Bonneville Power Administration and Pacific States Marine Fisheries Commission.

Yebra, D.M., S. Kiil, and K. Dam-Johansen. 2004. Antifouling technology — past, present and future steps towards efficient and environmentally friendly antifouling coatings. Progress in Organic Coatings 50(2): 75–104.

Zhang, H., R. Lamb, and J. Lewis. 2005. Engineering nanoscale roughness on hydrophobic surface—preliminary assessment of fouling behavior. Science and Technology of Advanced Materials 6(3-4): 236–239.

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