A Review of the
Use of Coatings to Mitigate Biofouling in Freshwater

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Executive Summary

In 2007, the quagga mussel, *Dreissena rosriformis bugensis*, and the zebra mussel, *Dreissena polymorpha*, established populations in parts of California and the Colorado River Basin. These freshwater mussels are capable of clogging screens and pipes and fouling hard substrates. They have cost municipal water districts in Nevada, Arizona and California millions of dollars for additional maintenance and led to several lake closures. If they become established in the Columbia River Basin (CRB), management costs at hydropower facilities may exceed $23 million/yr (Phillips et al. 2005). Combating the impacts of fouling mussels will require an integrated management plan that may include antifouling coatings to reduce mussel settlement and growth on vulnerable surfaces in hydropower facilities. Specialized coatings can be effective in controlling mussel fouling but coating effectiveness is a function of a number of interacting factors. This report provides a review of the factors that influence coating efficacy, evaluates coatings currently on the market, and recommends actions needed to identify coatings that could be applied to hydropower facilities in the CRB as part of an integrated mitigation strategy.

Hydropower facilities in the CRB are particularly vulnerable to macrofouling impacts by dreissenid mussels due to the dependence on once-through river water for raw-water cooled heat exchangers that are fed by concrete-embedded piping. In facilities located in infested locations, macrofouling by bivalves is most problematic on fixed screens and grates, gates used to regulate flow, smaller diameter intake conduits operated at capacity, and small diameter piping with flow velocities either continuously or intermittently less than 1.8 m/s.

There are many commercially available coatings, but our review suggests that many are not suitable for use on CRB facility components. Coatings based on foul-release mechanisms are effective and would limit initial settlement and strength of attachment, but are mechanically weak and are subject to failure due to detachment and abrasion. Heavy metal-based coatings are both effective and durable but work by releasing biocides such as copper into the surrounding water, which may impact native flora and fauna. In general, protective coatings such as coal tar, epoxy or other anti-corrosion anti-abrasion agents are not considered effective against mussel settlement.

Based upon available literature, coatings that are good candidates for immediate application on CRB facility components include two silicone- and one fluoropolymer-based foul-

release coatings: Bioclean SPGH (Chugoku Marine Paints), Smart Surfaces (Fuji Hunt Smart Surfaces), and Intersleek 900 (International Marine Paints). Effective copper-based coatings that require further study of copper leaching rates prior to any application in the CRB include copper, bronze, and brass metal, LuminOre (copper cold spray), and Epco-Tek 2000 (epoxy with copper powder). Zinc galvanizing is also a coating option, although studies show that it provides poor to moderate protection against freshwater macrofouling. It is important to note that this review was hindered by the availability of information. Many coatings lack long-term, objective assessment of their lifespan, durability, and performance; and access to existing data is sometimes hampered by confidentiality agreements and proprietary information.

Because of their cost, coatings are generally not used to mitigate mussel fouling on a large scale in freshwater facilities in North America. At best, coatings for mitigation of mussel fouling in the CRB will likely be one component of an integrated strategy. The large-scale use of coatings on CRB facilities could prove unnecessary or, more likely, not be economically feasible. Costs for silicone coatings estimated over a five-year period are $127/m^2$, and they have an effective lifespan of up to six years. If advances in coating development result in a lifespan greater than ten years, foul-release coatings may prove to be cost-effective for mitigation of macrofouling on CRB facility components like trash racks, intake bays, intake tunnels, and pump wells. If leaching rates are not environmentally damaging, copper coatings or inserts might be suitable for use in small diameter piping, fire protections systems, and condenser boxes; however, coating use is restricted to those facility components that are readily accessible and that can be thoroughly dried prior to application.

The following actions are recommended.

- Monitor ongoing research on mitigation of mussel fouling in the Colorado River. This research will likely be readily applied in the CRB.

- Begin lifespan and efficacy testing of Intersleek 900, Bioclean SPGH, Smart Coatings, Epco-Tek 2000, LuminOre, and thermal sprays of copper and copper alloy under the water chemistry regime in the CRB.

- Determine whether there are regulatory obstacles to use of anti-fouling coatings that contain biocides in the CRB.

- Attempt to gain access to long-term efficacy data that are currently unavailable due to confidentiality agreements.

- Increase efforts to prevent introduction of fouling mussels to the CRB. A delay in introduction may permit development of more cost-effective coating technology.

- Ensure that early detection and rapid response programs are funded to limit spread of new infestations.

- Expand ongoing research on the effect of dissolved calcium on mussel survival and growth to include the effect of food quality on growth. Better information on environmental influences on mussel growth will enhance the ability to predict where mussel fouling will have significant hydropower impacts.

- Develop more detailed cost analyses for mussel mitigation using coatings.

- Support evaluation of coatings with little performance data in freshwater systems.

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Introduction

The risk of a zebra or quagga mussel infestation in the Columbia River Basin is increasing. In 2007, the quagga mussel, *Dreissena bugensis*, and the zebra mussel, *Dreissena polymorpha*, became established in parts of California and the Colorado River Basin. With the discovery of multiple infestations of both mussels in California, the likelihood of an unintentional introduction in the Columbia River Basin increases as mussels are readily transported on infested boats and boat trailers. These freshwater mussels clog screens and pipes and foul hard substrates and have led to millions of dollars in additional maintenance costs for municipal water districts in Nevada, Arizona and California, as well as instigating several lake closures. If they become established in the Columbia Basin, management costs at hydropower facilities are expected to exceed $23 million/yr (Phillips et al. 2005).

Planning is critical to minimizing and mitigating the cost of an invasion of the Columbia River Basin. Combating the impacts of these fouling mussels will require an integrated management plan that includes anti-fouling coatings to reduce mussel settlement and growth on vulnerable under water surfaces such as screens and trash racks. Ackerman et al. (1993) demonstrated that the highest levels of mussel recruitment are on mild steel, PVC and concrete structures. Phillips et al. (2005) conservatively estimated the cost of applying anti-fouling paint to trash racks at $81,000 per generator (the estimate does not include the cost of labor/installation.). Other infrastructure may also be at risk for dreissenid fouling, which could lead to interference in the operation of hydropower facilities on the river.

Reactive and preventive methods are available for controlling macrofouling by *D. polymorpha, D. bugensis, Limnoperna fortunei*, and *Mytilopsis leucophaeata* in raw water systems (RWS). Reactive control methods include treating the water with chemicals and heat, manual cleaning, and the replacement of equipment (Boelman et al. 1997; Daling and Johnson 1984; Jenner et al. 1998; Miller et al. 1992). Preventive control methods include changing open-loop cooling systems to closed-loop, using source water free of mussels, using air-cooled equipment, mechanical filtration, and regular prophylactic treatments with chemicals and heat (Boelman et al. 1997; Daling and Johnson 1984; Jenner et al. 1998; Miller et al. 1992).

Specialized anti-fouling coatings can be effective in controlling zebra mussels in raw water systems but certain types of coatings may be more effective at some locations and on some

types of substrates and infrastructure than others. First invented in the 1600s, anti-fouling coating technologies have been widely applied in a variety of situations and substrates. Anti-fouling coatings are used primarily in marine habitats to protect the hulls of ships, but they are also a useful tool for minimizing fouling effects of freshwater dreissenid mussels. Choice of an appropriate coating requires consideration of efficacy of the coating, the material to be coated, flow conditions, scouring and other exposure, raw water impacts, and various operational constraints.

Until recently there were a limited number of anti-fouling coatings available. The most common type of anti-fouling coating is a surface paint that leaches a biocide into the water to repel organisms. In European water systems, which have been infested with invasive dreissenid mussels for centuries, toxic paints containing copper were used to prevent mussel fouling (Race and Kelly 1994). In recent decades, paints containing tributyl tin (TBT) were substituted for copper-based paints but evidence of acute toxicity from low levels of TBT led to a recent worldwide phase-out of those products. In response, many new coatings have been, or are being, developed including non-toxic coatings that rely on low-surface tension to create smooth/slippery surfaces. New developments in anti-fouling technology include the use of non-metal fouling repellants in traditional coatings, non-toxic foul-release coatings (ablative hydrophilic polymer films and low free surface energy films.), and thermal spray coatings (slow dissolution of metal ions repels fouling organisms) (Yebra et al. 2004).

An integrated treatment approach that which includes proven technologies, maintains operational flexibility, can be rapidly implemented, and is cost effective and dependable is key to an effective treatment and control program in the Columbia River Basin. This review focuses on potential coatings that could be incorporated in an integrated treatment plan. We provide a summary evaluation of conventional and non-conventional antifouling coating technologies for various types of water handling structures/substrates in the system.

To prepare this review we searched electronic databases, national and international journals, technical reports, proceedings, and research collected by previous surveys (see ZMIS USACE 2002) for information on the efficacy of various types of anti-fouling coatings. Much of the available literature summarizing the use of antifouling coatings for zebra mussel control a was conducted in the 1990s (see EPRI 1992) and does not reflect the advances in anti-fouling coatings in recent years that have been driven by the worldwide phase out of TBT anti-fouling

paint. To further inform this review power plants and researchers in North America were contacted to gain insight from their experiences with coatings and macrofouling. Companies manufacturing coatings were also contacted for experimental and case-study data on lifespan, durability, performance and cost, and to identify new products and check product availability.

This review primarily addresses fouling by the dreissenid mussels *Dreissena polymorpha,* and *D. rostriformis bugensis (D. bugenis hereafter).* Both dreissenids are invasive freshwater mussels that have caused extensive ecological and economic impacts in North America. Other mussels of potential concern include *Limnoperna fortunei,* and *Mytilopsis leucophaeata. Limnoperna fortunei* (golden mussel) is a freshwater mussel native to the rivers of eastern China and south-eastern Asian that has established populations in Hong Kong, Japan, Taiwan, Thailand, Korea, Argentina, Uruguay, Paraguay, Bolivia, and Brazil (Magara et al. 2001; Sylvester et al. 2005). *Mytilopsis leucophaeata* (false dark mussel) is a brackish water mussel native to the Atlantic and Gulf coasts of North America and is in the same family (Dreissenidae) as *D. polymorpha* and *D. bugensis*. *M. leucophaeata* is established in brackish water in The Netherlands, Belgium, France, Britain, Germany, and the Black Sea basins (Rajagopal et al. 2005b), but it has also been reported in freshwater (Conn et al. 1993; Rajagopal et al. 2005b; Verween et al. 2007).

Most North American research has focused on *D. polymorpha* and *D. bugensis* because these invasive mussels are established in the USA and Canada. *M. leucophaeata* and *L. fortunei*, however, have similar impacts to *D. polymorpha* and *D. bugensis* in areas they have colonized outside their native range. *M. leucophaeata* and *L. fortunei* could be more problematic in the Columbia Basin than *D. polymorpha* and *D. bugensis* because they have broader environmental tolerances (Boltovskoy et al. 2006; Karatayev et al. 2007; Laine et al. 2006; Rajagopal et al. 2005b; Verween et al. 2007). All of these mussels alter ecosystem structure and function at local and system-wide scales (Karatayev et al. 2007) and may deleteriously impact hydroelectric generation, irrigation, water conveyance, fisheries, and habitat and wildlife recovery. We note where control options for *M. leucophaeata* and *L. fortunei* differ greatly from those of dreissenid mussels but will refer to dreissenid mussels as the primary species of interest throughout this report.

Biofouling

There are over 4,000 species of organisms that cause biofouling in marine, brackish and freshwater environments. Most of these are microfoulers: bacteria, viruses, protozoa, fungi, and algae (Jenner et al. 1998; Yebra et al. 2004). The development of biofouling in aquatic environments typically follows a regular sequence of events: 1) development of a conditioning film, 2) microfouling, and then 3) macrofouling. The development of a conditioning film usually occurs in seconds (Whitehead and Verran 2009) and provides the linking layer between the fouling organism and the substrate surface. The composition of the conditioning film depends on the composition of the water and substrate but it typically develops with the adsorption of organic molecules (e.g. humic substances, polysaccharides and proteins) and ions on submersed substrates (Fleming and Ridgway 2009; Whitehead and Verran 2009).

Bacteria, fungi, viruses, algae and protozoa colonize the conditioning film on submersed substrates to form a biofilm. Bacteria and other microorganisms within the vicinity of the substrate initially attach to the conditioning film via electrostatic forces, hydrogen bonds and van der Waals forces (Murthy and Venkatesan 2009; Whitehead and Verran 2009). Initial cell attachment to the conditioning film is rapid and occurs over a period of several seconds to minutes (Whitehead and Verran 2009; Yebra et al. 2004). Secondary microfouling colonizers such as spores of macroalgae and protozoa attach to the conditioning film on submersed substrates in about a week (Yebra et al. 2004).

Microbial cell adhesion occurs after the initial attachment of the microoganisms. Microbes adhere to many different materials with a wide range of properties including aluminum, stainless steel, copper, synthetic polymers, and concrete. Initial adhesion is influenced by the chemistry and topography of the substrate surface, but the development of the biofilm changes the substrate surface properties (Whitehead and Verran 2009) and allows for further development of the biofouling community.

Microbes that adhere to a submersed substrate produce proteins, glycoproteins, glycolipids, extracellular DNA, polysaccharides, and other substances that are termed extracellular polymeric substances (EPS). EPS create a hydrated, heterogeneous matrix that hold the microbes together and bind the microbes to the submersed substrate surface (Fleming 2009). EPS moderates the influence of external factors (e.g., temperature, nutrient availability, water velocity, and substrate physical and chemical characteristics) on the biofilm development

(Murthy and Venkatesan 2009). It alters porosity, density, water content, charge, sorption properties, hydrophobicity, and the mechanical stability of the biofilm (Flemming 2009). The EPS also provides nutrients and suitable substrate for further colonization by diatoms and microalgae that, in turn, facilitates subsequent settlement of other organisms (Murthy and Venkatesan 2009).

Microbial biofilms become a nuisance when their development exceeds a tolerance threshold that allows them to damage materials and degrade component performance (Murphy and Venkatesan 2009). For example, biofilms in cooling water circuits restrict flow in pipes, decrease heat transfer in exchangers, enhance corrosion, and alter surface roughness (Lewandowski and Beyenal 2009; Murthy and Venkatesan 2009). Biofilms also alter the release of biocides from antifouling coatings (Valkirs et al. 2003).

Macrofouling is caused by the settlement, attachment and growth of invertebrate larvae on conditioning films or biofilms, translocating adults, and drifting shells and exoskeletons. Macrofouling is most abundant and troublesome in marine and brackish waters (Yebra et al. 2004). Macrofoulers tend to be filter feeders that form dense colonies, which means large quantities of nutrients and other material are removed from the water and deposited on or in the benthos (e.g. psuedofeces). This deposition increases further fouling by biological organisms and silt (Jenner et al. 1998). They also often have planktonic larvae that enhance dispersal capabilities and enable them to colonize areas that would otherwise be unavailable to the adult life stages.

The presence of microbial biofilms promotes the settlement and survival of polychaetes, hydroids, bryozoans, mollusks, tunicates and barnacles (Dobretsov et al. 2009), usually within two to three weeks (Yebra et al. 2004). Although microbial biofilms faciliate settlement and attachment of macrofouling organisms they are not a prerequisite for macrofouling. Macrofouling organisms tend to have rapid metamorphosis and growth rates and are highly adaptable to water temperature, flow patterns and salinity, and substrate type (Yebra et al. 2004).

Powerplant Impacts

Macrofouling affects powerplant operation and safety and can cause plant shutdowns (Boelman et al. 1997; Claudi and Mackie 1994; Jenner et al. 1998; Matsui et al. 2002; Neitzel et al. 1984; Ricciardi 1998). *D. polymorpha* macrofouling 5 to 8 cm thick developed on all surfaces of intake structures at the Detroit Edison Monroe plant in 1989 (Kovalak et al. 1993).

Macrofouling is difficult to control because the problems it causes are due to both living and dead mussels. These problems change rapidly with environmental parameters (e.g. water temperature) and plant operating conditions (e.g. water intake volume and flow velocity) (Neitzel et al. 1984). Therefore, macrofouling and its management are site-specific processes. Management of macrofouling varies according to the biology of the fouling organisms, and the physical and chemical characteristics of both the facility and the source water (Murthy and Venkatesan 2009).

Macrofouling organisms are a nuisance because they tolerate wide fluctuations in the environment, adhere to submersed surfaces, develop hard shells or exoskeletons, form dense colonies, produce planktonic larvae, filter-feed, and because of the large individual organism and/or colony size. Macrofoulers attach to concrete, metals, wood, plastics, and other synthetic polymers and materials, as well as other organisms (Ackerman et al. 1996; EPRI 1992; Kilgour and Mackie 1993). Dreissenid mussels are especially insidious macrofoulers because they can settle and attach to hard surfaces even in the absence of a microbial biofilm needed by many other fouling organisms.

Dense layers of macrofouling organisms increase operational and maintenance costs by causing blockage or reduction in water flows, mechanical damage, corrosion, and equipment failure (Venkatesan and Murthy 2009). Macrofouling also changes the physical and chemical characteristics of submersed substrates, which reduces water flow and the efficacy of antifouling biocides and coatings; increases siltation, corrosion, material loadings and frictional resistance and the settlement of other fouling organisms. When individuals or colonies detach from submersed substrates, their shells and exoskeletons cause mechanical damage, blockages, increased corrosion, and equipment failures.

Dreissenid mussel macrofouling and its management are a function of the biology of the mussel (see Appendix I). They cause fouling and management problems because they are small, fecund, grow rapidly and have short lifespans, filter-feed, and because they have planktonic larvae and sessile adults that attach to hard substrates in freshwater habitats. Their abundance and distribution are influenced by their physiological tolerances, growth and reproductive patterns, and the habitat.

Components of the RWS in hydropower facilities subject to macrofouling include piping, screens, valves, and other equipment related to the delivery of untreated lake or river water for

generator and turbine oil coolers, air coolers, turbine shaft seals, and fire protection (Boelman et al. 1997; Jenner et al. 1998; Miller et al. 1992; Neitzel et al. 1984). In addition to the RWS, other components of hydropower facilities vulnerable to fouling include turbine headcovers, trash racks, penstocks, gates, water intakes, pumping stations, instrumentation, navigational locks, chamber gates, spillway gates, culvert valves and racks, emergency closure and dewatering gates, concrete surfaces, and navigation aids (Abdul Azis et al. 2003; Boelman et al. 1997; Claudi 1995). Neitzel et al. (1984) found that if mussels were present in the source water used for the RWS, it was likely that the powerplant had fouling problems.

Macrofouling is problematic on fixed screens and grates, gates used to regulate flow, smaller diameter intake conduits operated at capacity, and small diameter piping with flow velocities either continuously or intermittently less than 1.8 m/s (Claudi and Mackie 1994; RNT 2009). Mussels attached to either copper or aluminum alloy conduits, however, are more sensitive to flow velocity than those growing on acrylic conduits. Trash racks and screens are ideal for settlement and growth; mussels readily attach to zinc-galvanized steel and food and oxygen is typically abundant (Jenner et al. 1998). Flow velocity and intermittency are the most important parameters affecting macrofouling due to the effect upon both the mussels' ability to settle, attach, survive and proliferate, as well as influence the efficacy of various control efforts (Jenner et al. 1998; Matsui et al. 2002). Water flow rate in RWS piping is typically within the mussels' tolerances (Boelman et al. 1997; Jenner et al. 1998; Venkatesan and Murthy 2009). In US nuclear power plants, 80% of the heat exchangers in freshwater open-cycle cooling systems exhibit flow conditions conducive for macrofouling (Neitzel et al. 1984). Most facilities operate with flow velocities of 2.0 to 3.0 m/s in piping and cooling water conduits, and maintained velocities of 1.4 to 1.8 m/s across the heat exchangers (Venkatesan and Murthy 2009).

Some areas of facilities are not favorable for colonization. Low flow areas, for example, accumulate silt, sediment, and corrosion products that limited colonization. Stagnant areas may also have low dissolved oxygen concentrations, and areas with high flow and turbulence prohibit settlement and attachment.

Effect of Operating Procedures

Operating procedures can promote or inhibit macrofouling. The design of the facility determines how operations influence fouling. Flow in conduits of the RWS and across screens and trash racks is determined by changes in plant operations. Important design considerations

include the configuration of facility components such as conduit diameter and length, joints, widening or constriction of conduits, changes in elevation, branching, elbows, valve design and valve malfunction, and substrate surface characteristics (Jenner et al. 1998; Neitzel et al. 1984; Venkatesan and Murthy 2009). Changes in plant operations that influence biofouling occur when redundant systems are used alternatively (e.g. for maintenance), intermittent systems are used (e.g. for testing and emergencies), RWS are backwashed, and when water hammers cause pressure changes (Neitzel et al. 1984).

Biofouling management activities are somewhat facility-specific because they must be integrated into routine operations and maintenance of facilities. Management of biofouling in freshwater facilities commonly include the use of screens, filters (e.g. high-flow microfiltration), chemical injection (e.g. chlorine), thermal backwashing, foul-release and biocide release coatings, and manual cleaning (Miller et al. 1992).

Effect of Facility Design and Configuration
The location of macrofouling within a facility is greatly influenced by flow patterns. Areas with intermittent flows are particularly prone to the settlement of planktonic veligers (Claudi and Mackie 1994; Miller et al. 1992). Intermittently used RWS, such as fire protection systems, are typically maintained full of raw water and periodically flushed during testing (Neitzel et al. 1984). Fire protection systems are sometimes used for other tasks (e.g. lawn sprinklers, general water hose). These additional uses increase the intermittency and hence risk (Miller et al. 1992). Ideally, fire protection systems should be filled with treated water or used infrequently to create stagnant, anoxic conditions unfavorable to mussel survival. Facility and component shutdowns allow settlement in conduits with normal flow rates that are high enough to prevent biofouling. When operations resume, the resulting flows provide the food, oxygen and waste removal necessary for extensive growth of the sessile mussels that are more tolerant of high flow rates than the settling veligers.

Flow velocity and intermittency greatly influence the efficacy of control efforts. High flow rates require input of large volumes of chemical control agents to maintain lethal concentrations and contact times. Flow patterns affect the efficacy and lifespan of biocide-based antifouling coatings and foul-release coatings (Yebra et al. 2004). Continuous flows and high velocities increase the dissolution rate of biocides and the surrounding coating matrix of ablative coatings, which decreases the coating lifespan (Jenner et al. 1998). Foul-release coatings perform

better under flowing conditions because the resultant force of the water actually removes the loosely attached macrofoulers (Yebra et al. 2004). High flow velocities, however, also reduce foul-release coating mass and cause delamination. Intermittent low velocity flows allow more settlement on foul-release coatings but reduce the dissolution rate for biocide-based and ablative coatings (Yebra et al. 2004).

Component Size

The effect of component size on water velocity is usually not limiting to dreissenid macrofouling. These small mussels can firmly attach to pipes, walls, and other structures using byssal threads (Claudi and Mackie 1994; Neitzel et al. 1984). Macrofouling by these mussels occurs readily on large components such as intake structures and raw-water supply headers, as well as on small components such as small diameter piping, heat-exchanger tubes and tube sheets (Neitzel et al. 1984). Larger components increase the surface area available for colonization and provide a source of downstream veligers (Jenner et al. 1998; Miller et al. 1992). Deleterious impacts from fouling, however, are often exacerbated in smaller RWS components that are more susceptible to clogging and erosion compared to the intake tunnels and other larger structures (Claudi and Mackie 1994; Neitzel et al. 1984).

Conduit Length and Configuration

Macrofouling densities are influenced by the length of piping and distance from source water as this alters flow patterns and concentration of dissolved oxygen and food. Magara et al. (2001) reported that *L. fortunei* abundance decreased with longitudinal distance along pipes in Japanese water treatment plants. The greatest densities of macrofouling tend to occur in the initial 152 to 305 m of intake pipes (EPRI 1992). Colonization is often greater on the downstream side of screens located at the point of entry into a conduit than in areas further into the system (Miller et al. 1992; Neitzel et al. 1984).

The configuration of conduits affects flow patterns and the resultant macrofouling because sudden widening of conduits reduces flows and areas of constriction increase flow velocities. Matsui et al. (2002) found that macrofouling by *L. fortunei* was reduced in water transmission pipes in branched sections, possibly due to increased flow and turbulence. Low elevation areas and areas with sudden changes in flow direction trap both living and dead mussels (Neitzel et al. 1984). Elbows create heterogeneity in the water velocity and cause

turbulence, which results in greater fouling on the walls of the inner curved regions of an elbow (Jenner et al. 1998; Matsui et al. 2002).

Component Accessibility

The accessibility of components influences macrofouling, its control, and the availability and efficacy of maintenance options. Access to components is determined by design features such as removable screens; the ability to dewater; and conduit size, length, and branching. Raw water intakes located at shallow-water and mid-water depths may have more macrofouling compared to deep water intakes due differences in the distribution of veligers and adult mussel food resources in the water column (RNT 2009).

Valves

Valves are important in macrofouling because they allow intentional flow control, represent a constriction, and are common sources of leaks. Valve leaks are a primary source for the continuous, low-velocity flows needed to maintain the dissolved oxygen and food supply to sustain veligers in intermittently used RWS (Neitzel et al. 1984; Miller et al. 1992). Neitzel et al. (1984) reported that leaking is greatest with butterfly and gate valves; globe and ball valves are the least likely type of valve to leak. Areas of constriction in valves, such as the valve seat, are susceptible to clogging and enhanced erosion due to blockages (Claudi and Mackie 1994; Neitzel et al. 1984).

Light

Light has direct and indirect effects on macrofouling. *D. polymorpha* exhibit strong negative phototaxis (Kobak et al. 2009; Toomey 2002) and show a preference for shaded versus sunlit surfaces (Marsden and Lansky 2000). Light indirectly influences fouling through its effects on water temperature and phytoplankton abundance (Yebra et al. 2004).

Substrate Orientation

The three-dimensional orientation of surfaces within facilities influences macrofouling abundance. *D. polymorpha* have a strong preference for the upper versus the under side of horizontal substrates (Marsden and Lansky 2000), and prefer the upper surface of horizontal substrates over vertical surfaces. (Kilgour and Mackie 1993; Marsden and Lansky 2000). *D. polymorpha* did not exhibit a preference of horizontal over vertical surfaces in tanks where light was excluded (Eckroat et al. 1993).

Substrate Materials

Substrate materials have a greater impact on the settlement and translocation patterns of *D. polymorpha* than light, substrate orientation, and texture (Marsden and Lansky 2000). *D. polymorpha* and *D. bugensis* colonize most construction materials used in North American facilities, especially concrete, carbon steel, and stainless steel (Ackerman et al. 1996; EPRI 1992; Kilgour and Mackie 1993; RNT 2009). Copper and zinc resist macrofouling, while other metals are fouled to varying degrees (Marsden and Lansky 2000).

Source Water

The source water for RWS and other facility components influence macrofouling and its management. Open-loop cooling systems are typically used in freshwater facilities where large volumes of relatively clean, noncorrosive raw-water are available from a river or lake (Neitzel et al. 1984). Closed-loop cooling systems are typically used in saltwater-cooled plants due to the corrosive nature of saltwater and the long-recognized macrofouling threat in brackish and marine systems (Neitzel et al. 1984). Closed-loop cooling systems, however, are used in freshwater plants such as Oconee and Palo Verde, in part, to reduce macrofouling (Neitzel et al. 1984). Treated municipal water has been used in closed-loop cooling systems of small facilities.

The use of source water for recreational boating increases the risk of macrofouling. Johnson and Carlton (1996) and Karatayev et al. (2007) demonstrated that overland transport of mussels attached to recreational watercraft is a primary vector for mussel introduction. The continued discovery of trailered watercraft with attached mussels in the Columbia Basin, and throughout the western US, corroborate the importance of this vector and illustrate the vulnerability of source waters and hydropower facilities to increased biofouling with increased use from trailered recreational boating.

Chemical parameters of the source water that influence macrofouling and its control in hydropower facilities include pH, salinity, concentrations of calcium, magnesium, chlorophyll a, nitrogenous compounds, dissolved oxygen and other gases, hardness, organic and other macromolecule loadings, reaction and diffusion rates, degradation rates and pathways, particulates and colloidal matter (absorbing biocides), and pollution (Jenner et al. 1998; USEPA 2003; Yebra et al. 2004). The solubility and bioavailability of biocides (e.g. cuprous oxide) is influenced by pH and hardness (USEPA 2003; Yebra et al. 2004). Furthermore, the solubility of rosin used in production of antifouling coatings increases dramatically with increasing pH, which

results in a high biocide release rate and subsequent reduced lifespan for the antifouling coating (Yebra et al. 2004).

Nutrient concentrations, organic compounds, and dissolved gases influence macrofouling and its control. In general, there is a positive relationship between macrofouling and nutrient concentrations (Jenner et al. 2009; Venkatesan and Murthy 2009). For example, *D. polymorpha, D. bugensis* and *L. fortunei* required dissolved calcium to build a calcite shell. Dissolved oxygen reduces antifouling properties of rosin-based, copper-biocide antifouling coatings by causing the oxidation of dissolved copper (I) and the partial re-precipitation of copper (II) carbonate, copper (II) chloride or copper (II) hydroxide. Organic pollution indirectly affects growth and treatment methods through its impact on nutrient and dissolved oxygen concentrations. Organic and other macromolecule loadings also influence the development of conditioning films that are a prerequisite for macrofouling, form complexes with biocides, and alter the free-energy of substrate surfaces (Yebra et al. 2004). Additionally, particulate and colloidal-matter adsorb biocides and can alter reaction and diffusion rates that determine biocide release rates from coatings (Yebra et al. 2004).

Coatings

Antifouling coatings have a long history and are an important option for managing macrofouling. Antifouling coatings such as pitch, tar and wax have been used to control macrofouling on marine vessels for over 2000 years (Yebra et al. 2004). Antifouling coatings utilizing copper as a biocide have been widely used for the last 200 years (Abdul Azis et al. 2003; Brady 2005). The advent of iron ships, and the resultant corrosion from copper fueled the development of coatings composed of a biocide embedded in a polymer coating (Yebra et al. 2004). Tributyl-tin containing, self-polishing antifouling coatings and foul-release type coatings were first patented in the mid 1970s (Brady 2005; Chambers et al. 2006; Yebra et al. 2004). These coatings dominated the polymer coating industry until the International Maritime Organization (IMO) banned their use on 1 January 2008 due to their leaching of biocide and subsequent environmental impacts (Brady 2005; Chambers et al. 2006; Champ 2000; Yebra et al. 2004). Current efforts are directed at improving existing, and developing new, foul-release and other less toxic antifouling coatings (Brady 2005; Chambers et al. 2006; Omae 2003; Yebra et al. 2004).

Most coating systems are based on paints, including enamels, lacquers, varnishes, undercoats, surfacers, primers, sealers, fillers, stoppers and other materials (Chambers et al. 2006). Most of the available paint-based coating systems are categorized as self-polishing copolymers (SPC), controlled depletion polymers (CDP), and foul-release (Chambers et al. 2006; Yebra et al. 2004)[1]. Other commercially available antifouling systems not based on paints included metals and electrical antifouling systems (Chambers et al. 2006; Omae 2003). Electrical coating systems are not covered in this review.

Antifouling Coatings

Coatings used on marine vessels and offshore marine platforms are typically SPC and CDP coatings. Biocides are incorporated into SPCs and CDPs, resulting in antifoulant properties due to the occasional sloughing off of the eroded coating, and the embedded biocides. Biocides are attached as pendant groups to the copolymer and include smaller groups like zinc and copper or larger groups such as N-methacrylimidazole of heterocyclic amines, and 2,4,6-tribromophenyl methacrylate of aromatic halides (Brady 2005; Chambers et al. 2006; Omae 2003). When the labile pendant groups are released from the hydrophobic SPC copolymer via hydrolysis, they leave a hydrophilic site on the polymer (Brady 2005). When enough hydrophilic sites have accumulated, the water soluble section of the SPC polymer self-polishes by sloughing off, exposing a fresh paint surface (Brady 2005). CDP coatings contain a biocide embedded in a soluble matrix. Rosin-derived compounds are the typical soluble binders used in CDPs (Yebra et al. 2004). As the rosin-derived compounds react with ions present in the water and release resinates, the embedded biocides are concomitantly exposed and released (Yebra et al. 2004).

Antifouling coating systems may also be based on metals. Metal antifouling systems include heavy metals, as well as alloys and compounds of these metals (Omae 2003). Heavy metal antifouling systems are represented as solid metals (e.g. molten zinc) or as a powdered form incorporated into a coating matrix (Omae 2003). There are numerous ways to incorporate metals into antifouling systems including galvanization, and thermal-spray. Thermal-spray or metallized spray coatings are made by spraying molten metal onto a substrate using compressed

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[1] It was difficult to evaluate SPC and CDP coatings separately due to a lack of available data regarding the underlying antifouling mechanisms. Both SPC and CDP use the term self-polishing, which refers to the hydrolysis/ablation of the coating polymer. The term hydrolysis describes reactions where H^+ ions replace a group/atom on a functional group, and since these reactions involve other ions (e.g. potassium), the term alkaline hydrolysis is more accurate (Yebra et al. 2004). The term hydrolysis is used in this report to refer to both, however, due to its widespread use in the available literature.

air. Metal wire can be melted using either an oxygen-acetylene flame or an electric arc (Miller et al. 1992). Copper is the most commonly used antifouling metal (Omae 2003); other antifouling metals include aluminum and zinc (Race and Kelly 1994). Copper alloys used for macrofouling include brass, bronze, aluminum bronze and aluminum brass (Omae 2003; Race and Kelly 1994). There are numerous copper compounds used for antifouling, including inorganic compounds (e.g. Cu_2O, Cu_2S, CuS), organo-copper compounds (e.g. PhCu, $Me(CH_2=CH)CuLi$), and chelated compounds (e.g. copper pyrithione, ethylenediamine copper aluminum) (Omae 2003). Zinc and zinc alloys are also used in freshwater antifouling coating systems (Skaja 2009).

The efficacy of different antifouling coatings varies with target species (Casse and Swain 2006). Copper is highly effective against macrofouling, but is readily colonized by microfoulers such as algae. For this reason, booster biocides are often used in conjunction with biocides such as copper (Omae 2003). Zinc is more toxic to many freshwater organisms than it is to marine organisms (Race and Kelly 1994).

Coatings that rely on labile biocides are registered with the US Environmental Protection Agency (USEPA). It is possible that copper-based antifouling coatings will face environmental regulations similar to tributyltin coatings, and coatings that release heavy metals may require NDPES permits in the future.

Copper Toxicity
The release rates of copper from antifouling coatings, after initial loss, are variable and range from 3.0 to greater than 20 $\mu g/cm^2/day$ (Srinivasan and Swain 2007; Valkirs et al. 2003). Copper leaching rates, measured *in situ* directly from vessel hulls coated with antifouling coating that contained low concentrations of copper in the Pacific Ocean, range from 3.8 to 8.2 $\mu g/cm^2/day$ (Valkirs et al. 2003). Although copper is a micronutrient at low concentrations, the release of copper is regulated by the USEPA (USEPA 2003). The proposed freshwater criterion continuous concentration (CCC) and criterion maximum concentration (CMC) for dissolved copper are 1.9 $\mu g/L$ and 3.1 $\mu g/L$, respectively (USEPA 2003). These proposed CCC and CMC are based on a biotic ligand model, and are not a function of water hardness. The CCC, chronic criteria, is the four-day average concentration not to be exceeded more than once every three years. The CMC, acute criteria, is the one-hour average concentration not to be exceeded more than once every three years. Naturally occurring concentrations of copper in oxygenated surface freshwater ranged between 0.1 and 2.0 $\mu g/L$ (USEPA 2003; Naimo 1995). Copper, however, can become toxic at higher concentrations. The toxicity of copper is related to its bioavailability, which is difficult to determine because it is influenced by numerous site specific parameters such as pH, dissolved organic carbon, temperature, dissolved inorganic carbon and major cations and anions (USEPA 2003; Srinivasan and Swain 2007). Copper occurs naturally in two valence states, cuprous (Cu^+), and cupric (Cu^{2+}) (Srinivasan and Swain 2007). Cupric copper is the more toxic valence state due to its bioavailability (Srinivasan and Swain 2007). Although toxic concentrations of copper in oxygenated surface waters are uncommon in North America, these metals accumulate in surficial sediments while most dissolved metals are absorbed onto suspended particles (Naimo 1995). Copper concentrations between 5 and 25 $\mu g/L$ could be lethal for marine and freshwater invertebrates (Chambers et al. 2006; Naimo 1995). The USEPA regulations for copper in drinking water stipulate a limit of 1,000 $\mu g/L$ (Chambers et al. 2006)

Foul-release Coatings

Foul-release coatings are considered environmentally friendly and provide fouling protection by two basic mechanisms: the hydrolysis of polymers that 1) remove fouling with the eroded coating layer and 2) minimizing the initial attachment and the strength of attachment through the properties of the coating surface. Conventional SPCs lack biocides and are typically acrylic or methacrylic copolymers that hydrolyze in water (Omae 2003). The hydrolysis of the coating surface removes the attached macrofouling, and exposes a fresh, smooth coating surface. Some commercially available biocide-free conventional SPC coatings show toxic effects that is derived from the paint and eluates of the paint (Löschau and Krätke 2005; Watermann et al. 2005). Zinc has been detected in conventional SPC coatings that claim to be biocide-free, and it appears that zinc oxide is an integral ingredient controlling SPC coating ablation (Löschau and Krätke 2005; Watermann et al. 2005). Foul-release coatings that do not contain biocides provide properties of the coating surface that minimize the strength of attachment between the organism's adhesive surface interface and the adhesive water interface (Chamber et al. 2006). This type of foul-release coating develops fouling but the strength of bond is weak and can be broken by the force of flowing water or by light cleaning. These coatings represent the bulk of commercially available foul-release coatings, and are referenced as foul-release hereafter.

Foul-release coatings are less regulated than coatings that release biocides. The USEPA ruled that duplex foul-release coating systems are not subject to the provisions of the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA); 7 USC 136 et seq. (PL 95-396) (Jones-Meehan et al. 1999). Foul-release coatings are termed nontoxic and this term is used hereafter in this review. Contaminants such as silicone oils are released from foul-release coatings, however, silicones are largely inert and no toxic effects have been observed (Aubert et al. 1985; Carpenter et al. 1995; Craig and Caunter 1990; Henry et al. 2001; Nendza 2007; Powell et al. 1999; Stevens et al. 2001; Watermann et al. 2005), these substances could be toxic under certain conditions and may require further evaluation (Chapman 2001).

The efficacy of different foul-release coatings varies by target species. Hydrophilic surfaces are more effective against protein and cell adhesion while hydrophobic surfaces are more effective against macrofouling (Callow et al. 2004; Krishnan et al. 2008). Most

commercially available foul-release coatings contain homogeneous hydrophobic topcoats with properties like low surface energy, non-polarity and elasticity.[2]

Commercially available foul-release coatings generally employ multiple layers and mixtures of components to improve adhesion and corrosion protection. Topcoats are generally slippery and rubbery to reduce adhesion between macrofouling and the underlying coating/ substrate. A tough, water-resistant anticorrosive layer, often an epoxy, is used to protect the base substrate and augment the adhesion of the topcoat. These multiple layers with very different properties are the origin of the term duplex systems. Adhesion of the topcoat to the anticorrosive layer presents a challenge, especially for silicone-based coatings. Manufacturers use various tie coats to bond the tough bottom layer to the hydrophobic topcoat, catalysts, solvents, and curing times to improve adhesion. These features are closely guarded proprietary information. Coatings also differ in chemical formulations and the type and amount of free oils and other additives.

Silicones and flouropolymers are the two main types of hydrophobic foul-release coatings commercially available (see Appendix II). Silicone- and fluoropolymer-based foul-release properties are different due to different fracture mechanisms.[3] Essentially, the rubbery nature of silicones causes a weak bond that fractures by peel. Fluoropolymers encompass a large group of compounds, but are basically thermoset polymers based on compounds made from carbon bonded to fluorine.[4] The ability to foul is minimized by the very low surface energy of fluoropolymers but, because of its higher modulus (i.e. it is less mobile), greater force is required for interfacial fracture, which occurs by shear (Brady 2005; Yebra et al. 2004).

Commercially available silicone-based, foul-release coatings appear to function better than their fluoropolymer counterparts, despite the fact that fluoropolymers offer greater

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[2] In general, the performance of hydrophobic foul-release coatings against macrofouling is determined by the surface free energy, elastic modulus, non-polarity, and the coating thickness (Brady 2005; Krishnan et al. 2008). Surface free energy is the polymer property most frequently correlated with the low energy fracture of biological adhesives (Brady and Singer 2000). The Baier curve describes the relationship between relative adhesion and the surface free energy. According to the Baier curve, adhesion is minimized at surface free energies between 20 and 25 mN/m (Yebra et al. 2004). In general, coatings with surface free energies less than 20 and greater than 30 mN/m show poor foul-release properties (Yebra et al. 2004). Elastic modulus describes the tendancy of a surface to be deformed elastically when force is applied. The elastic modulus influences the mechanism of interfacial fracture (Brady 2005). Coating thickness controls the fracture mechanics of the interface (Yebra et al. 2004). For example, the coating thickness influences whether a fracture occurred by peel or shear (Brady 2005).

[3] The silicone-oxygen bonds within silicone-based polymers allow motion between the coating functional groups, and this motion prevents the functional groups of the macrofouler adhesive to remain proximate to and form dipolar or hydrogen bonds with the copolymer groups (Brady 2005; Brady and Singer 2000).

[4] Fluoropolymers are characterized by densely-packed, highly cross-linked, and well-organized groups within the copolymer (Brady 2005). These characteristics result in a stable, non-porous, smooth surface that resists coating molecule rearrangement and macrofouler adhesive infiltration (Brady 2005).

mechanical strength than silicones (Brady 2005; EPRI 1992; Leitch and Puzzuoli 1992). Ontario Hydro and the Electric Power Research Institute (EPRI) performed numerous panel experiments and small-scale trial applications of coatings, and had the best success against *D. polymorpha* and *D. bugensis* macrofouling with silicone-based coatings (EPRI 1992; S. Poulton, pers. com.). The cost of silicone-based coatings over a five year period (installation, materials, labor, maintenance, and disposal) were estimated in 1999 to range between $108/m^2 and $127/m^2 (Gross 1997; Jones-Meehan et al. 1999). EPRI (1992) estimated the application costs, including material and labor, for one commercially available silicone-based foul-release coating to be $44/ m^2 for concrete, and $55/ m^2 for steel. Recoating was generally half the initial application costs (EPRI 1992).

Organizations and Agencies Involved in Coating Evaluation

A number of facilities have performed panel experiments and/or trial applications of antifouling and foul-release coatings. These facilities were identified through peer-reviewed literature, government reports, personal communications, and the application history of Bioclean SPGH, which was provided by Chugoku Marine Paints (CMP). The following agencies and organizations were contacted:

- USACE lock and dam facilities in Buffalo, Chicago, Detroit, New York, Tulsa and Vicksburg districts, the Paint Techonology Center, and the Construction Engineering Research Laboratory
- USBOR dams on the lower Colorado River and the Science and Technology Program at the Denver Center
- MWD staff in the Materials and Metallurgy Team and the Water Quality Laboratory
- Ontario Hydro and Consumers Energy resource specialists and operations and maintenance staff.

We were unsuccessful in contacting Algonquin Power, Hydro Québec, BC Hydro, Tampa Electric, Florida Power and Light Company, Commonwealth Edison, and Carolina Power and Light.

CMP, LuminOre, and E Paint coating companies provided information. CMP was the most cooperative coating company contacted, and provided by far the greatest amount of performance and lifespan data. LuminOre and E Paint also provided information regarding lifespan, durability, application, and performance data collected through case studies and/or company claims. The companies are willing to provide coated panels to demonstrate durability and performance. Unsuccessful attempts were made to obtain information from Devoe Coatings,

International Marine Coating and Nippon Paint, FujiFilm Hunt Smart Surfaces, Jotun Group, Kansai Paint, Pettit Paints, and General Electric.

A list of facilities and details of their experiences with antifouling coatings is available in Appendix III.

Coating Evaluation

The many commercially available coating systems differ in their performance against macrofouling, lifespan, durability, environmental impacts, and cost. Candidate coatings to mitigate macrofouling in CRB facilities were identified through a sequential elimination process. Any coating system proposed for use in CRB facilities must be effective against macrofouling, anticorrosive, environmentally acceptable, economically viable, exhibit a long lifespan, be compatible with the underlying substrates and other undercoatings, resist abrasion and biodegradation, have a smooth surface, and be capable of antifoulant protection under various facility operational conditions. Acceptable coating systems can not be toxic, produce substances that are persistent in the environment, be chemically unstable, and must be relatively inexpensive.

Coatings Eliminated Due to Performance, Availability, or Application Problems

Coatings were eliminated from further consideration if they showed poor performance against bivalve macrofouling, are no longer commercially available, or if there are significant problems with application (e.g. handling radioactive materials). Coating performance was determined from panel and grate experiments and/or trial applications on vessels and power plant components. Coatings eliminated from further consideration in this review according to these criteria are listed in Table 1.[5]

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[5] Coatings eliminated from further consideration in this review could be effective against macrofouling in the future. New formulations, or vintages, of a coating listed on Table 1 could improve its performance and new information could become available that demonstrated greater efficacy. For example, earlier versions of Intersleek (International) were not effective (Gross 1997), but the Intersleek 900 system showed good performance against macrofouling (P. Drooks, pers. com.; Skaja 2009). For this reason, the source of the performance evaluations used was provided in Table 1. The more recent evaluations captured the current coating formulation/vintage. Greater consideration was given to the more recent evaluation, therefore, in the event of conflicting reports, and in these cases the coating was marked with +. These performance evaluations were limited by sample size, variable methods, and were conducted over a 12 year period. Performance was often evaluated using one experiment. Lastly, macrofouling was site specific and products that showed acceptable performance in one location could fail in another, and vice versa.

Table 1. Foul-release (a), antifouling (b), protective (c), and hybrid coatings that were eliminated from further consideration in this review.

a)

Coating Name	Company	Type	Reason	Source
AF Biosuper SI	Usagida Chem. Ind.	silicone resin	3	6
Biox	Kansai Paint	silicone	1	3, 11
Duflon 100 Fresh	Nippon Paint Co.	fluoroplastic	3	6
Duflon Fresh Top Clear	Nippon Paint Co.	fluoroplastic	3	6
Duflon K300	Nippon Paint Co.	fluoroplastic	3	6
EC-4300	Ecological Coatings	unknown	3	1
EXSIL 2200	General Electric	silicone	1	4, 7
Kai Clean	Dai Nippon Toryo Co.	silicone resin	3	6
RTV11	General Electric	silicone	1	4, 7
S-1	Nippon Paint Co.	silicone resin	3	6
Scatt	Release Ind.	fluoropolymer	3	11
Slipstream	Synthetic Lubricants	silicone grease	3	11
Wearlon	Ecological Coatings	silicone epoxy	3	11

b)

Coating Name	Company	Type	Reason	Source
Awlstar	US Paint	SPC-unknown	3	11
Barnacl X	Enviro Coatings	epoxy-Cu	3	11
capsaicin		nontoxic irritant	3	11, 12
Cathacoat 304	Devoe Coatings	epoxy-inorganic Zn	3	1
Cathacoat 304L	Devoe Coatings	epoxy-inorganic Zn	3	1
Cathacoat 313	Devoe Coatings	epoxy-organic Zn	3	1
Copper Clad	Ferro Corporation	epoxy-Cu powder	1	13
+copper-nickel alloy (90/10)		metal	3	1, 12
Magnetic fields		magnetic fields	3	10
modified isophthalate polyester		unknown-Cu powder	3	12
NoFoul ZDF	E Paint	hydrogen peroxide paint	3	11
piezoelectric coatings		electrical systems	2	5
Sea Coat	Donar Chem.	tacky paint-Cu	3	11
Sealife	SeaLife Corp.	unknown-Cu oxide	3	1
Sunwave Plus	E Paint	nontoxic antifouling	3	1
thallium 204		radioactive coating	2	1
tin		metal	3	12
waterborne acrylic coating		copper sulfate	3	12
+zinc galvanizing		metallic coating	3	2, 9
+zinc thermal sprayed on steel		metallic thermal spray	3	1, 2
zinc/ Al metallizing on steel		metallic thermal spray	3	1, 2
ZO-HP	E-Paint	nontoxic antifouling	3	1

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Table 1. Continued.

c)

Coating Name	Company	Type	Reason	Source
2000 PW	Novacoat Pty Ltd	protective coating	3	1
Arcor	Arcor Chem.	epoxy	3	11
Chosui Coat	Sigma Shintu Co.	epoxy resin	3	6
coal tar epoxy		protective coating	3	2
Concrete Coat	PermaDri Inc.	asphaltic material	3	1
ETON 2300 NB	Kawakami Paint	epoxy resin	3	6
Irathane	Devcon	polyurethanes	3	11
Kubota Powder TK 1413	Kubota Corp.	epoxy resin	3	6
ML 3000	Dai Nippon Toryo	polyurethane resin	3	6
polyamide coatings		protective coating	3	2
polyamide zinc coatings		protective coating	3	2
polyethylene		plastic	3	2, 8, 11, 12
polyurethanes		polyurethanes	3	2, 11
polyvinyl chloride		plastic	3	8, 11
Simsite	Simsite Chem.	epoxy	3	11
Suiyou 4000	Kawakami Paint	polyvinyl resin	3	6
Superglide	Belzona	epoxy	3	11
Ureall RIM PD-30	Kawakami Paint	polyurethane resin	3	6
Vtop Kai Free	Dai Nippon Toryo	polyurethane resin	3	6

d)

Coating Name	Company	Type	Reason	Source
4500 S	Plastite	epoxy-flakes	3	1
Scatt with added antibiotic	Starbrite Co.	fluoropolymer-unknown	3	11
SN-1	E-Paint	fluoropolymer resin-unknown	3	1
Ureall RIM PD-30 with Ag	Kawakami Paint	polyurethane resin-Ag	3	6
Plastisol	DMX Co.	polyurethane-red pepper	3	11

Notes:

Reason for elimination: (1) product was no longer available, (2) there were application problems, (3) poor performance in panel/ grate experiments and/ or trial applications on vessels and power plant components

Data sources: (1) Skaja 2009, (2) P. Drooks, pers. com., (3) D. Innis, pers. com., (4) Wacker Silicones, pers. com., (5) Yebra et al. 2004, (6) Matsui et al. 2002, (7) Jones-Meehan et al. 1999, (8) Meyer et al. 1994 (9) Kelly 1998, (10) Jenner et al. 1998, (11) Gross 1997, (12) Race and Kelly 1994, and (13) B. Devine, pers. com.

Coatings Eliminated Due to Lack of Freshwater Studies

Additional coatings were eliminated from further consideration because they are manufactured and used for application on marine vessels and offshore structures, and they release biocides such as heavy metals, copper and zinc. The coatings presented in Table 2 are marketed for these marine offshore applications and lack available data regarding performance against freshwater bivalve macrofouling.

Table 2. Antifouling coatings eliminated from further consideration because they contained biocides marketed for offshore application on marine vessels and platforms and because they lacked available experimental performance data at freshwater facilities.

Coating Name	Company	Type
Amercoat 70ESP	Amercoat	unknown
Sea Grandprix 1000/2000	CMP Chugoku	SPC-unknown biocide
Sea Grandprix 500/700	CMP Chugoku	SPC-unknown biocide
SeaTender 10/12/15	CMP Chugoku	CDP-unknown biocide
TFA 10/30	CMP Chugoku	CDP-unknown biocide
Globic 81900-81970	Hempel	SPC-Cu pyrithione
Oceanic 84920-84950	Hempel	SPC-unknown biocide
Olympic 86950/1	Hempel	SPC-unknown biocide
Olympic HI-76600	Hempel	SPC-unknown biocide
Interclene 245	International	contact leaching-unknown biocide
Intersmooth Ecoloflex SPC	International	SPC-Zn pyrithione
Interswift 655	International	Hybrid-Cu pyrithione
Interspeed 340	International	CDP-Zineb
Sea Guardian	Jotun Group	SPC-unknown biocide
Sea Prince	Jotun Group	SPC-unknown biocide
Sea Queen	Jotun Group	SPC-unknown biocide
SeaQuantum	Jotun Group	SPC-Cu pyrithione
Exon	Kansai	SPC-unknown biocide
Nu Crest	Kansai	CDP-unknown biocide
Nu Trim	Kansai	SPC-unknown biocide
Envoy TF 400/500/600	Leigh's Paints	SPC-unknown biocide
Exion TF 700/701	Leigh's Paints	unknown
Grassline M396	Leigh's Paints	unknown
Trinidad	Pettit Paint	epoxy-Cu
Ultima	Pettit Paint	SPC-cuprous oxide
Unepoxy Plus	Pettit Paint	epoxy-cuprous oxide
Vivid	Pettit Paint	unknown
Alphagen 10-20-50	Sigma Coatings	SPC-isothiazolone
Altha Trim	Sigma Coatings	unknown
Sigmaplane Ecol/ HA	Sigma Coatings	SPC-isothiazolone
Cleanship 2.91-2.97	Transocean	unknown
Optima 2.30-2.36	Transocean	CDP-unknown biocide

Coatings Eliminated Because Their Use is Limited to Marine Systems

Coatings in Table 3 demonstrated excellent to good performance against macrofouling in panel/grate experiments and/or trial applications on facility components, but were eliminated from further consideration in this review because they contained biocides marketed only for offshore applications on marine vessels and platforms.

Table 3. Antifouling coatings eliminated from further consideration because they contained biocides marketed for offshore application on marine vessels and platforms.

Coating Name	Company	Type	Source
Horizons	Pettit	SPC-cuprous oxide	Gross 1997
Micron CSC	International	SPC-Cu	Gross 1997
Tin-free AF	Chugoku Marine P	SPC-Cu	Gross 1997
MIL-P-15931	various	vinyl resin-Zn and cuprous oxide	Race and Kelly 1994
Sigmaplane Ecol	Sigma Coatings	SPC-Cu and unknown	Matsui et al. 2002
Ecoflex SPC 600	Nippon	CDP-Cu and unknown	Matsui et al. 2002
AF Biosuper HG	Usagida Chemical	silicone resin-Ag	Matsui et al. 2002

Ranking of Performance of Selected Coatings

Product lifespan, durability, efficacy, and environmental compliancy were reviewed for the coatings that had at least fair performance and environmental compliance. Comparisons between coatings were complicated by inconsistencies in the materials and methods used for performance evaluations as well as the lack of available information about the products. The lifespan, durability, performance, and environmental compliance characteristics of the possible coatings were ranked according to criteria in Table 4 and summarized in Table 5.

Potential Coatings for Use in CRB Facilities

Based on the evaluations summarized in Table 4, the candidate coatings that could be immediately used in CRB facilities to mitigate macrofouling are Bioclean SPGH, Smart Surfaces, and Intersleek 970. The lifespan, application, durability, and performance of these three coatings are reviewed in detail below.

Bioclean SPGH

Bioclean SPGH is a nontoxic silicone-based foul-release coating produced by Chugoku Marine Paints (CMP). The next generation foul-release product from CMP is Bioclean Echo, which is a high-solid, low-VOC coating. Bioclean Echo is not yet commercially available (T. Birdwell, unpublished data). Bioclean DX is an old coating formulation/vintage that was discontinued several years ago. The Bioclean SPGH coating involves application of an epoxy primer and silicone elastomer with fillers. It is unknown if Bioclean SPGH contains free oils, but Bioclean DX contains exuding oils (Gross 1997).

The lifespan of Bioclean will likely exceed five years. Trial applications of Bioclean DX on LILCO coastal facility components showed an effective lifespan of six years (Gross 1997). Case studies provided by CMP showed that Bioclean SPGH has a lifespan of five years on trash

racks and intake bays of freshwater and coastal facilities, and a lifespan of seven to nine years on intake tunnels. According to CMP, the difference in lifespan observed between intake tunnels and the trash racks/intake bays is due to water flow patterns (T. Birdwell, unpublished data). According to the Bioclean application history, provided by CMP, six utilities reapplied Bioclean on 17 units, and the mean lifespan for these applications based on the date of renewal and initial application is 75 months (SD= 20 mo., min= 44 mo., max= 118 mo., n=17). Most renewal jobs were done on intake tunnels (58%, n=14) and intake bays (29%, n=7). The other renewal applications were done on boats (8%, n=2) and service water pumps (4%, n=1) (T. Birdwell, unpublished data).

Table 4. Ranking and criteria used for assessing coating a) durability, b) performance, and c) environmental compliancy.

a)

Rank	Durability Criteria
1	Excellent = hard, damage unlikely, excellent resistance to abrasion, no evidence of delamination
2	Good = medium to hard, damage possible but good resistance to abrasion and wear, no delamination
3	Fair = soft to medium, damaged relatively easy, care taken with handling, some resistance to abrasion, some evidence of delamination
4	Poor = soft, easily damaged, evidence of serious damage and/or delamination

b)

Rank	Performance Criteria
1	Excellent = none or very few scattered mussels attached, easily removed
2	Good = few individuals to isolated patches, easily removed
3	Fair = mussels in patches but significantly less than controls, not easily removed
4	Poor = mussel coverage > 50%, difficult to remove

c)

Rank	Environmental Compliancy Criteria
1	Excellent = no biocide present in topcoat, no FIFRA registration
2	Good = biocide in topcoat but release rates very low, use in CRB possible
3	Fair = biocide in topcoat, measurable release rates, unknown if allowed in CRB
4	Poor = biocide used in topcoat, used on marine vessels and offshore structures, not expected to be allowed in CRB

According to unpublished data provided by T. Birdwell, Bioclean coatings are mostly applied to concrete (55%, n=76) and steel (30%, n=41) substrates, with fewer applications to stainless steel (5%, n=7), cast iron (4%, n=5), fiberglass (3%, n=4), rubber (2%, n=3) and copper coated concrete (1%, n=2). The most common components coated with Bioclean in North American facilities are the intake tunnels (45%, n=61), intake bays (23%, n=31), and trash racks (10%, n=14). Between January 1988 and October 2008, Bioclean coatings were applied to intake wells (6%, n=8), cell blocks (4%, n=6), tug boats (3%, n=4), derrick barges (1%, n=2), service water pumps (1%, n=2), screen wells (1%, n=2), and intake canals, fire pumps, debris filters,

pump housing and piping, and intake bay pump-deck annulars (<1%, n=1, respectively). The mean surface area coated per application in the period between 1988 and 2008 was 1,028 m^2 (SD= 1,395 m^2, range= 6,627 m^2, n=116). Omae (2003) noted that Bioclean SPGH was used for circulation water pipes and aqueduct pipes for Japanese power plants.

Table 5. Lifespan, durability, performance and environmental compliance for foul-release and antifouling coatings that had at least fair performance against bivalve macrofouling, and exhibited at least fair environmental compliancy. Evaluations were based on experiments conducted independent of coating companies (Exp), case studies presented by coating companies (Case), and coating company claims (Claims). Lifespan and the time period associated with a performance evaluation are in years. Durability, performance and environmental compliance are ranked according to criteria presented in Table 4. Separate evaluations of the same coating that were done in different studies are shown on separate lines, and different performance evaluations over time within the same study are on the same line but separated by a comma. Blanks indicated no data were available.

Product	Lifespan (yr)			Durability (1-4)			Performance over years (1-4)						Environ Comp (1-4)
	Exp	Case	Claim	Exp	Case	Claim	Exp	T_{Exp}	Case	T_{Case}	Claim	T_{Claim}	
Bioclean SPGH	6	5-9	5-9	3	3		1 1 1	0.5 1.5 6.0	1	5-9			1
Smart Surfaces			5	3		3	1	1.0	1	0.5			1
Intersleek 970			5	3		3	1	1.2			2	5	1
DEVCLEAR							2	2.0					1
Sigma LSE							2	1.5					1
Nipple Sleek							2	1.5					1
Epco-Tek 2000	5 6		10-20	1 1		1	1 2 , 3 3, 4	6.0 3, 4 1, 2					3
Luminore				1		1	2 2 1	5.0 1.3 1.3	1	1			3
copper metal[NC]							1 1 1 1	1.3 1.3 3.0 1.5					3
brass metal[NC]							1 1	1.3 1.5					3
bronze metal[NC]							2	1.5					3
aluminum-bronze metal[NC]							3	1.3					3
copper thermal spray[NC]							1	1.3					3
brass thermal spray[NC]							1	1.3					3
bronze thermal spray[NC]							1	1.3					3
zinc galvanizing[NC]	8			1			3 3	1.5 1.3					2 2

NC = coating lacked a specific manufacturing company, and hence no case studies or company claims were made.

Surface preparation and proper application are important for Bioclean SPGH performance. Improper application contributed to a coating failure at Hudson Lighting, TX, where the coating delaminated and clogged facility components. Prior to application, units are shutdown, dewatered, existed fouling scraped away, and surfaces dehumidified – surfaces must

be dry for application. The component to be coated must be large enough for a man to enter the space. The minimum diameter conduit that has been coated with Bioclean SPGH is 0.7 to 0.9 m. An epoxy primer, such as Umeguard MP must be applied first, and then the silicone topcoat is applied (T. Birdwell, unpublished data). It was unknown if a tie coat or proprietary additives are used to promote adhesion of the coating layers. The typical coat thickness was 0.150 mm. The work area must be sealed to contain solvent fumes. CMP contractors that are supervised on-site by CMP representatives do the applications (T. Birdwell, unpublished data).

Bioclean SPGH has fair durability. It is soft, and therefore susceptible to abrasion. It incorporates silica fillers to reinforce and strengthen the coating matrix, but there is a compromise between the foul-release mechanisms and coating matrix strength. Bioclean SPGH is best used in flow velocities between 0.9 to 1.2 m/s. Water velocity significantly greater than 3.0 m/s could wear away Bioclean SPGH (T. Birdwell, unpublished data). Gross (1997), however, noted that Bioclean DX showed good resistance to waterborne debris. Bioclean DX applied to intake bays and intake tunnels at coastal facilities showed no loss of adhesion or delamination for six years, except in areas where the concrete was not properly sealed (Gross 1997).

Bioclean SPGH showed excellent performance against marine and freshwater macrofouling. Intake bays and tunnels coated with Bioclean DX remained fairly clean for six years in a coastal hydropower facility. There was essentially no fouling after one year in the intake bays, and only a small amount of cleaning was necessary after the second year. The coated intake bay performance was not degraded until after five years and recoating was done after six years. The coated intake tunnel was clean for six years. In comparison, intake tunnels without coating, were heavily fouled after six months (Gross 1997). Bioclean was effective against *Balanus amphitrite* cyprid settlement *in vitro,* and macrofouling in static and dynamic *in situ* panel experiments conducted in marine waters for six months (Watermann et al. 1997). Matsui et al. (2002) evaluated densities of *L. fortunei* mussels that settled on panels placed in flowing conditions within the Nagara and Yodo Rivers and in the Daido Water Intake Pumping Station for 15 to 18 months. They also conducted laboratory experiments to evaluate the density of *L. fortunei* juveniles and adults that attached to panels in static tanks. Bioclean SPGH showed the second lowest density of attached mussels of the nineteen coatings tested. The only two coatings with performance comparable to Bioclean SPGH, were antifouling coatings containing copper.

In two of the three field experiments and all three of the laboratory experiments, no mussels attached to Bioclean SPGH coated panels.

Smart Surfaces

The Smart Surfaces Duplex Fouling Release system is a nontoxic silicone-based foul-release coating manufactured by FUJIFILM Hunt Smart Surfaces (FHSM) under a license to the patent holder, NRL. The Smart Surfaces system includes epoxy primers, a tethering agent in the epoxy coat to promote adhesion, a tie coat and a room temperature vulcanized (RTV) silicone topcoat that contains proprietary free silicone oil.

The long-term lifespan of Smart Surfaces is unknown, however, according to FHSM the lifespan of Smart Surfaces in power plants is five years, and a lifespan greater than five years is possible. FHSM claims an effective lifespan of approximately 12 years (1996 to March 2008) for Smart Surfaces-coated concrete intake tunnels at the Dominion Energy Brayton Point facility.

Substrate preparation prior to application is important for this product. Depending upon initial substrate condition, preparation varies from high-pressure water cleaning to abrasive blasting. According to FHSM, Smart Surfaces can be applied to primed steel, aluminum, fiberglass, and concrete substrates using standard, airless spray equipment, brushes, or rollers. Airless spray application is recommended. According to FHSM, metal substrates are prepared using SSPC-SP6 commercial blast cleaning or SSPC-SP12 water jetting to WJ-2.

FHSM presented four case studies of the application of Smart Surfaces to power plant components including concrete intake tunnels at the Eemshaven plant of the Electrabel Company and the Brayton Point plant of the Dominion Energy, as well as the trash racks at the DC Cook Nuclear Plant of American Electric Power Company and the Northport Steam Generating Station of National Grid. In the two case studies presented by FHSM that involved application to power plant trash racks, the metal was abrasive blasted to SSPC-SP10 Near White. Abrasive blasting to SSPC-SP13 was done for concrete applications in the FHSM case studies. According to FHSM, the desired concrete surface profile depth was 3.0 mm. The minimal substrate surface and ambient air temperatures for application of the Smart Surfaces tie coat and topcoat are 4°C and 30% humidity. The maximum ambient air and substrate surface temperatures for application are 32°C and 38°C, respectively, at 80% humidity.

Smart Surfaces coating involves four coats. According to FHSM, the dry film thickness per coat generally ranges from 0.152 to 0.305 mm. The first coat onto bare substrate is an

immersion grade epoxy primer. The second coat is another immersion grade epoxy primer that has a tethering agent added to promote adhesion. The third coat is the FHSM tie coat, which varies in thickness depending upon the underlying substrate depth profile. The Smart Surfaces topcoat is the fourth coat and this coat thickness varied as well. In the case studies presented by FHSM, the coating film thickness of the Smart Surfaces tie coat and topcoat are greater for concrete substrates. Naphtha is used to thin the Smart Surfaces topcoat and clean equipment. According to FHSM, Smart Surfaces cures via solvent release.

The Smart Surfaces coating can be repaired. Small scratches restricted to the topcoat are the easiest to repair. The scratched area can be cleaned with a thinner to remove surface contaminants and recoated with the FHSM silicone topcoat. Repairing damage that exposes the underlying coats or bare substrate is more complex. The damaged area must be treated as a new application, and preparation is done accordingly to the bare substrate. The underlying coats (epoxy coats, tethering agent and tie coat) are applied to only the damaged area. According to FHSM, the silicone topcoat should overcoat the topcoat surrounding the damaged area.

FHSM Smart Surfaces is soft and generally not considered very durable (Skaja 2009). It had fair durability in short-term USBOR and MWD experiments (P. Drooks, pers. com.; Skaja 2009), but apparently lasted 8 to 10 years in Ontario Hydro experiments before blistering (A. Skaja, pers. com.). Recent experiments by USBOR and MWD in the lower Colorado River showed minimal damage to the edges, corners and face of the panels and grates coated with Smart Surfaces after almost a year of immersion (P. Drooks, pers. com.; Skaja 2009). One grate coated with Smart Surfaces showed major abrasion damage, but this was attributed to placement (Skaja 2009). FHSM claims that Smart Surfaces applied to the intake tunnels at Brayton Point facility have been trouble-free for approximately 12 years. On its website, FHSM mentions a five-year warranty for Smart Surfaces coatings as long as a FHSM technical representative was present during application. Product information sheets mention a limited warranty for product defects for one year after purchase.

FHSM Smart Surfaces coating is effective against *D. polymorpha* and *D. bugensis* macrofouling. Ontario Hydro evaluated FHSM Smart Surfaces and other coatings for an excess of ten years, and although these data and reports are not available, FHSM Smart Surfaces was the only coating specifically mentioned by Ontario Hydro staff when asked about their long-term experiences with coatings (S. Poulton, pers. com.). Smart Surfaces coated panels and grates in

USBOR and MWD experiments showed excellent performance for approximately one year. In these trials, Smart Surfaces remained essentially free of *D. bugensis*, while there was concomitant fouling on other structures in the lower Colorado River during the 2008 to 2009 period (P. Drooks, pers. com.; Skaja 2009). Field trials conducted and presented by FHSM in Lake Ontario, showed similar findings to USBOR and MWD. According to FHSM, one hundred Smart Surfaces coated panels placed in Lake Ontario for six months remained *D. polymorpha* or *D. bugensis* free and the attached biofilms and algae were removed with water velocities as low as 0.15 m/s.

Intersleek 970

Intersleek 970 is a nontoxic fluoropolymer finish coat used in the Intersleek 900 foul-release system manufactured by International Marine Coating and Nippon Paint (International). According to International, the Intersleek 900 foul release system was originally designed for deep-sea, high activity vessels, but it could be applied to static structures such as power station water inlets. The Intersleek 900 foul-release system includes an anticorrosive primer layer, Intergard 264, a tie coat layer, Intersleek 731, and the finish coat, Intersleek 970.

A lifespan of five years is claimed for the Intersleek foul release coating system. The Intersleek 900 foul-release system was first applied to a marine vessel in 1987 and 230 vessels were coated by 2002 (Omae 2003). International reports that a drydocking intervals up to five years is possible with the Intersleek 900 system.

It is unknown if the Intersleek 900 system could be applied to concrete. According to International Marine Paints and Skaja (2009), Intersleek has been applied to metal substrates. Standard airless spray equipment is recommended to achieve the maximum film build in one coat. Rollers and brushes could be used but multiple coats would be required to achieve proper film build. According to International, over-application of the different coats extends application time and reduced foul-release properties. Bare substrate surfaces should be clean, dry and free of contamination. The substrate surface must be at least 3$^\text{o}$C above the dew point, and between 21$^\text{o}$ to 27$^\text{o}$C for optimum application properties. According to International, problems with curing and intercoat adhesion occur if application is made at low temperatures (less than 5$^\text{o}$C) or high humidity. Ambient air temperatures greater than 10$^\text{o}$C are ideal for application. According to International, the typical dry film thickness per coat is 0.15 mm. International GTA007 and GTA822 are used for cleaning equipment.

According to International, the Intersleek 900 foul-release system can be repaired. Areas of damage or breakdown are prepared using power tools or abrasive blasting to bare substrate. The entire coating scheme is then applied to the patch area. The Intersleek 900 topcoat can be applied over itself.

The Intersleek 970 topcoat showed fair durability. Flouropolymers are typically more durable than silicones, but Intersleek 970 still has a soft rubbery finish. According to International, the Intersleek 900 system is resistant to direct impact but is susceptible to mechanical damage via gouging or scraping activities. International recommended the use of nylon slings over chains during installation to avoid damage. A grate coated with Intersleek 970 was damaged within two months of immersion at a USBOR dam on the Lower Colorado River, but this damage was attributed to the grate rubbing against the trash rack structure due to the rope suspension deployment of the test grate (Skaja 2009). Parallel experiments conducted at intake structures on Lake Mohave by MWD did not show damage to Intersleek 900 coated grates that were secured in place (P. Drooks, pers. com.).

The long-term antifouling performance of the Intersleek 900 foul-release system is unknown but panel and grate experiments showed excellent short-term performance. Intersleek 970 performed very well in panel and grate experiments conducted by USBOR and MWD after 14 months immersion in the Lower Colorado River. A few *D. bugensis* mussels were observed attached to metal panels and grates coated with the Intersleek 900 system, but these mussels were easily removed (Skaja 2009; P. Drooks, pers. com.). Intersleek was effective against macrofouling for a period of six months in static and dynamic panel experiments in marine waters – over 64% of the surface was free of macrofouling in static conditions, and 97.4% was free of macrofouling in dynamic conditions (Watermann et al. 1997). International maintains the 'Dataplan' performance monitoring system, but these data are not publicly available. International claims that Intersleek 970 is effective for five years on marine vessels. Intersleek 970 was applied to some vessels or parts of vessels on the Carnival, Norwegian, Disney and the Royal Caribbean Cruise Lines (Srinivasan and Swain 2007).

Coatings to Explore Further

There are several foul-release, protective, and antifouling coatings with little available information and that require additional investigation. These products, the manufacturer, and the type of coating are shown in Table 6. The reasons for the recommended further review are varied

and include limited coating information and questions regarding performance, toxicity, and commercial availability. A summary of information available for some of the products is provided below.

DEVCLEAR

DEVCLEAR showed good performance against macrofouling in a panel experiment conducted in the 1990s, but additional and more current information is lacking for this coating. DEVCLEAR 278 is a nontoxic silicone polymer finish coat for the DEVCLEAR foul-release system manufactured by Devoe Coatings (Devoe). The DEVCLEAR system involves a multipurpose epoxy BAR-RUST 23, an intermediate coat, and the DEVCLEAR 278 topcoat. Devoe recommends the DEVCLEAR system for water intake pipes at electrical power plants and wastewater plant clarifiers. According to Devoe, the DEVCLEAR system can be applied to both steel and concrete using either standard air spray or airless spray equipment. The DEVCLEAR system is applied to completely dry surfaces and Devoe recommends removing previously painted surfaces. New concrete should be cured for a minimum of 30 days prior to application. According to Devoe, the DEVCLEAR system is generally applied in four coats at 0.125 to 0.2 mm per coat. Application to metal requires a multi-purpose epoxy coating, BAR-RUST 231. PRE-PRIME 167 Penetrating Sealer is required for application to bare concrete. The DEVCLEAR system can be applied when ambient air temperatures are greater than 4°C. The lifespan of the DEVCLEAR foul-release system is unknown. Gross (1997) reported that an earlier version of DEVCLEAR foul-release system performed well on panels into the second year of immersion.

Table 5. Foul-release, protective, and antifouling coatings that require further review.

Product	Company	Type
DEVCLEAR	Devoe Coatings	silicone polymer
Sigma LSE	Sigma Shinto Coatings	silicone polymer
Nipple Sleek	Nippon Paint Company	silicone polymer
Epco-Tek 2000	Hi-Tek Company	epoxy-Cu powder
Luminore	Luminore	cold-spray/metallizing-Cu
copper metal		metal
brass metal		metal
bronze metal		metal
copper-nickel alloy (90/10)		metal
copper thermal-spray		metal thermal-spray
brass thermal-spray		metal thermal-spray
bronze thermal-spray		metal thermal-spray
zinc galvanizing		hot-dip or electrocoat-Zn
Polyshield Aqualastic	Cygnet Enterprises	polyurea elastomer
SeaLion	Jotun Group	silicone foul-release
Rilsan	Arkema Inc	fusion bonded nylon
Kynar 500	Arkema Inc	PVDF resin
Fluon ETFE	Asahi Glass Company	thermoplastic fluoropolymer
Neoflon	Daikin Industries	perfluoroalkoxy resin
Teflon-FEP	DuPont	fluorinated ethylene propylene
Sylgard 184	Dow Corning Corporation	silicone elastomer
Mille light	Hempel	nontoxic ablative
Micron Eco	International	nontoxic ablative
SSC-44	US Gloss	nontoxic ablative
Lefant H2000	Lotréc AB	physical growth repellent
Hempasil X3	Hempel	hydrogel silicone foul-release
ECOLOSILK	Nippon Paint	biocide-free antifouling
SigmaGlide	Sigma Coatings	silicone foul-release
fibre flock		
electrical systems		
sacrificial substrates		

Sigma LSE and Nipple Sleek

No information was found for Sigma LSE and Nipple Sleek beyond the performance evaluation conducted by Matsui et al. (2002). Sigma LSE Finish is a silicone-based foul-release coating made by Sigma Shinto Coatings Ltd, which was incorporated into PPG Protective and Marine Coatings. Nipple Sleek is a silicone-based foul-release coating manufactured by the Nippon Paint Company. Matsui et al. (2002) evaluated the performance of Sigma LSE and Nipple Sleek against *L. fortunei* in panel experiments conducted in the Nagara and Yodo Rivers as well as the Daido Water Intake Pumping Station in Japan. Sigma LSE and Nipple Sleek were both effective against *L. fortunei* mussels, although they were not as effective as Bioclean (Matsui et al. 2002). Sigma LSE and Nipple Sleek both showed relatively low levels of

colonization during panel experiments conducted in flowing water for 15 months (Matsui et al. 2002).

Epco-Tek 2000

Epco-Tek 2000 requires further review regarding the environmental compliance of its copper leach rates. Epco-Tek, manufactured by Hi-Tek Coatings Company (Hi-Tek), consists of an epoxy primer undercoat and successive layers of epoxy mixed with copper powder. It appears that copper is released from surface layers through diffusional leaching. In a three-year static panel experiment, the copper leach rates from Epco-Tek 2000 were generally between 1.0 and 3.0 $\mu g/cm^2/day$, but leach rates as high as 8 $\mu g/cm^2/day$ were measured (Kelly 1998; Race and Kelly 1994). An unidentified commercially available epoxy with copper exhibited a mean passive copper leaching rate of 4.32 $\mu g/cm^2/day$, and a peak leaching rate of 18 $\mu g/ cm^2/ day$ immediately following mechanical cleaning (Schiff et al. 2004). The passive leaching rate returned to approximately 4 $\mu g/cm^2/day$ three days after mechanical cleaning (Schiff et al. 2004). Another unidentified commercially available epoxy with copper exhibited *in vitro* leaching rates between 1.6 and 7.0 $\mu g/cm^2/day$ in 16 mL/ min flow after a 48 hour conditioning soak (Cottrell et al. 2000).

The lifespan of Epco-Tek 2000 is up to five years in coastal power plants (Gross 1997) and six years in freshwater (Miller and Freitag 1992). Coating thickness is related to the lifespan of Epco-Tek 2000, and periodic mechanical sanding or blasting reactivated the surface to offer continued antifouling protection (Gross 1997). A coated vessel hull, however, was protected from macrofouling for six years without reactivating the surface through mechanical cleaning (Miller and Freitag 1992). Hi-Tek Coatings Company claims a lifespan of 10 to 20 years, and offers a warranty for 6 years with performance guaranteed by American Insurance Group (AIG).

Epco-Tek 2000 is compatible with multiple substrates. Epco-Tek 2000 was successfully applied to concrete, cast iron and fiberglass components of a coastal facility, including intake bays, pipes, and condenser inlet water boxes. Loose material on the substrate surface should be removed by sandblasting prior to application (Gross 1997). Hi-Tek recommends a 12/20 grit media for surface preparation, and spray application of the coating. Epco-Tek 2000 is applied in ambient temperatures of 21°C. A low-viscosity 100% epoxy primer undercoat is first applied to the bare substrate at a thickness between 0.025 to 0.051 mm. Five coats of the epoxy-copper coating are then applied at a thickness ranging from 0.432 to 0.508 mm (Miller and Freitag

1992). After curing, the topcoat is activated by mechanical blasting or sanding to expose copper (Gross 1997; Miller and Freitag 1992).

Epco-Tek 2000 is durable. It forms a hard, smooth, scratch-resistant and flexible coating (Miller and Freitag 1992). According to Gross (1997), Epco-Tek 2000 is resistant to physical damage and did not peel from underlying substrates.

Epco-Tek 2000 is effective against macrofouling in both fresh and marine environments. Epco-Tek 2000 was completely effective at preventing *D. polymorpha* settlement on a vessel hull that was operated in the Great Lakes for six years (Miller and Freitag 1992). It was effective against macrofouling on concrete intake bays following activativation by sanding and blasting. Epco-Tek 2000 that was sanded provided good antifouling performance for the first three years and fair performance for four years. Epco-Tek 2000 that was blast-activated provided excellent performance for the first three years and good performance for up to five years (Gross 1997). An unidentified copper pigmented epoxy coating evaluated by USACE in a steel and concrete panel experiment at Black Rock Lock was slightly fouled after 15 months immersion (Race and Kelly 1994). An unidentified epoxy with copper provided good macrofouling protection in a panel experiment for three years (Dorman et al. 1996).

Epco-Tek 2000, however, showed poor to fair performance in some evaluations. Epco-Tek 2000 performed poorly in a panel study done in the Great Lakes region (Kelly 1998). In that study, it showed low densities of attached *D. polymorpha* for over 200 days, but then was steadily colonized, and densities peaked at 500 mussels/m^2 after approximately two years. Gross (1997) reported that approximately half of the Epco-Tek coated surface area of a concrete intake bay of a coastal facility was moderately to heavily fouled after one year. This fouling, however, was attributed to improper blasting (i.e. activation) by the installation contractor (Gross 1997).

LuminOre

LuminOre also requires further review regarding the environmental compliancy of its copper leach rates. LuminOre, made by the LuminOre Company, is a copper composite metal antifouling coating that containes between 75 to 95% copper metal. LuminOre is not a suspension system like Epco-Tek 2000. Copper particles in LuminOre are surrounded by non-conductive, dielectric insulator binder molecules. The mode of action for LuminOre is unknown, but LuminOre is registered with the USEPA as an antifoulant. LuminOre claims it leaches copper at a rate of 1.9 μg/cm^2/day in freshwater (T. Valente, pers. com.).

LuminOre is compatible with a variety of materials. A dielectric insulator is required for substrates such as steel gates that could carry electric charge. LuminOre is also compatible with concrete, although concrete sealers are required to maintain hydrostatic pressure and surface preparation is necessary to remove sharp edges. LuminOre cannot be applied to silicone, unsealed Styrofoam, Teflon®, and some epoxies. It is applied by LuminOre staff using a cold metallizing spray process with standard high-volume low-pressure (HVLP) sprayers, rollers, brushes, or by pouring it onto a surface or casting in molds. LuminOre can be repaired with spot shooting (T. Valente, pers. com.).

The Corrosion Engineering Laboratory at MWD evaluated LuminOre in taper tests and concluded that LuminOre was one of the densest materials evaluated (P. Drooks, pers. com.). LuminOre showed good retention, memory and was flexible, and did not exhibit shrinking. According to T. Valente of LuminOre, it is highly abrasive resistant.

LuminOre is effective against macrofoulers including *D. polymorpha* and *D. bugensis*. MWD collaborated with Michigan water districts in the 1990s to assess *D. polymorpha* macrofouling through panel experiments that included LuminOre (P. Drooks, pers. com.). Although no empirical data are available, it is believed that the panels are still in place and effective at preventing new settlement. It appears, however, that translocating adults colonized these panels in Michigan. MWD began panel and trash rack trials in the lower Colorado River several years ago, concomitantly with USBOR, to evaluate the efficacy of coatings, including LuminOre, against *D. bugensis* (Skaja 2009). In these trials, LuminOre was evaluated in low and high flow areas along with other antifouling coating systems. LuminOre was applied to a dry film thickness of 0.203 mm on top of a 0.508 mm epoxy barrier. According to these trials, LuminOre worked well in still water and higher flow areas, however, it was reported to work better in low to no flows (A. Skaja, pers. com.). Long-term performance data were unavailable, but LuminOre is currently being studied by USBOR and MWD (Skaja 2009). According to the company, LuminOre showed no encrustation after one year of immersion in marine trials conducted at the University of North Carolina-Wilmington.

Costs of LuminOre depends on material and labor costs. According to the company, material costs are expected to range between $32/m^2 and $43/m^2. Material costs vary by volume purchased and size and configuration of the area to be coated. For example, both material and labor costs are scalable, and decrease with large jobs. Trash racks are more expensive both in

terms of labor and materials compared to a large continuous surface such as an intake bay tunnel due to the numerous gaps that lead to product waste and angles that require more labor (T. Valente, pers. com.).

LuminOre is not NSF60 or NSF61 registered. These registrations ensure products do not contribute contaminants to drinking water that caused adverse health effects. LuminOre refused to release certain proprietary information to apply for the NSF registration. MWD is trying to obtain a special permit from the state of California to apply LuminOre (P. Drooks, pers. com.).

Copper Metal and Alloys

As with the copper-containing products described above, copper and copper alloy metals and thermal-sprays require further review regarding the environmental compliancy of the copper leach rates. The reported leach rates from copper metals and thermal-sprays are variable, and this variability was affected by biofilm development, water temperature, water flow, age and condition of metal, and other factors (Srinivasan and Swain 2007; Valkirs et al. 2003). The steady state leaching rate in flows greater than 8 mL/min for pure copper metal and 90/10 copper/nickel after 48 hours pre-conditioning, and 190-hour immersion, are 2.6 and 1.9 μg/cm^2/day, respectively. Pure copper metal panels immersed in Lake Erie for five years at 16 mL/min flows had leach rates between 2.0 and 2.5 μg/cm^2/day (Cottrell et al. 2000). Steady state leach rates measured *in situ* from copper panels after 800 days immersion ranged between less than 3.0 to 5.0 μg/cm^2/day (Valkirs et al. 2003). The biofilms that develop on copper metals (Dormon et al. 1996) moderate the copper leach rate, which results in high variability between *in situ* and *in vitro* experiments as well as between measurements taken from panels and vessel hulls (Valkirs et al. 2003). Copper leach rates, therefore, are much higher following disturbance or upon initial coating immersion. Copper leach rates from initial coating immersion, measured from *in situ* panels ranged between 5.0 and 30 μg/cm^2/day (Valkirs et al. 2003).

Pure copper, brass, bronze, and copper-nickel metal could be applied as plates, piping, and inserts to facility components, and thermal-sprays using molten copper, brass, or bronze could be applied to a variety of facility components. Copper and its alloys, however, cannot be directly applied to all materials. For example, copper causes accelerated corrosion of carbon steel (EPRI 1992).

Copper and copper alloy metals and thermal-sprays have a long lifespan. This lifespan was expected to be greater than five years based on panel experiments that showed copper leach

rates above the threshold to prevent macrofouling for five years (Cottrell et al. 2000; Valkirs et al. 2003), however, an effective lifespan of three years was found for copper metal and its alloys containing above 80% copper in panel experiments conducted in Lake Erie (Cottrell et a. 2000). The reduced lifespan with in-lake exposure was due to colonization by biofilms. EPRI (1992) recommends inspections of copper coatings on intervals of 12 to 18 months for accelerated corrosion, and the development of biofilms.

Copper, brass, bronze, and copper-nickel metal and thermal-sprays are effective against freshwater macrofouling. Cottrell et al. (2000) demonstrated that efficacy was due to the leaching and availability of copper ions. Copper coated panels that had steady state release rates of 2.6 $\mu g/cm^2$/day were essentially free of mussels after 15 months immersion in Lake Erie, however, the effective copper release rate to accomplish macrofouling control appeared to be approximately 1.9 $\mu g/cm^2$/day or lower. (Cottrell et al. 2000). A variety of substrates and panels coated with copper and copper alloys with more than 80% copper were essentially free of *D. polymorpha* for three years, and copper-nickel alloys were free of D. *polymorpha* macrofouling after three years as long as the copper content was 90% or greater (Dormon et al. 1996). Panel experiments conducted in the lower Colorado River showed that copper, brass, and bronze metal are effective against *D. bugensis* for a period of 15 months. Over the 15-month period no mussels attached to the copper metal panel, while only a few adults and juveniles attached to the brass and bronze metal (Skaja 2009).

Zinc Galvanizing

Zinc galvanizing requires further review because it received mixed performance evaluations against macrofouling and the potential toxicity of zinc. Zinc galvanizing is done via hot-dip or electrocoat processes. The steady-state leach rate for zinc ions after 1.6 year *in vitro* immersion was approximately 5 $\mu g/cm^2$/day (Race and Kelly 1994). Zinc is more toxic to freshwater organisms than to marine organisms (Race and Kelly 1994). The leach rates for zinc, however, tend to be below maximum chronic concentrations determined by USEPA (1987).

Leitch et al. (1992) reported that statically charged zinc panels provide excellent protection for two years. Race and Kelly (1994) and Skaja (2009) reported that zinc galvanizing offered a degree of protection but was fouled by *D. polymorpha* and *D. bugensis*. For example, Skaja reported that zinc galvanized panels was colonized by a few *D. bugensis* mussels after 15 months immersion in a low flow area, but grates in a high flow area were 50% blocked in the

same period. Kelly (1998) and Drooks (pers. com. 2009) reported poor performance against both *D. polymorpha* and *D. bugensis.* Zinc galvanizing was identified by the USACE Zebra Mussel Research Program as a likely coating candidate in spite of its moderate antifouling performance due to its widespread use for corrosion protection, cost, simplicity, and lack of environmental regulation.

Coatings Currently Under Evaluation by USBOR

Several protective and fluoropolymer coatings listed in Table 6 are currently being evaluated in panel and grate experiments being conducted on the lower Colorado River. These coatings included Polyshield Aqualastic, Rilsan, Kynar 500, Fluon ETFE, Neoflon, and Teflton-FEP. In general, protective, and to a lesser extent, fluoropolymer coatings provided poor protection against macrofouling in other experiments (P. Drooks, pers. com.; EPRI 1989; Gross 1997; Matsui et al. 2002; Skaja 2009). The performance of these coatings is often related to surface energy and elastus modulus. USBOR efforts are focused on evaluating coatings that are more durable than the soft, but effective, silicone-based coatings (Skaja 2009).

Foul-Release Coatings That Lack Information

Several foul-release coatings require further review because basic coating information and performance evaluations are lacking. These coatings include SeaLion, Sylgard 184, Hempasil X3, ECOLOSILK, and SigmaGlide. A researcher at the Combinatorial Materials Research Laboratory at North Dakota State University suggested looking into Hempasil X3 (D. Webster, pers. com.). Hempasil X3 foul-release system features hydrogels on a solid silicone topcoat. According to Hempel Hempasil X3 has been applied to 32 marine vessels between 2007 and 2009.

Nontoxic Coatings with Reported Toxic Effects

Several coatings termed nontoxic are reported by Karlsson and Eklund (2004) to release toxins that are detrimental to aquatic life. These coatings included Millelight, Micron Eco, SSC-44, and Lefant H2000. Lotréc manufactured Lefant H2000, which incorporated a natural antifoulant compound produced by a marine sponge (Chambers et al. 2006).

Future Directions for Foul-release and Antifouling Coatings

Coatings chemists have not yet failed any challenge, and we may look to the future with

anticipation of the marvelous coatings yet to be invented.

- R.F. Brady Jr.

The problems caused by fouling are persistant and costly and researchers continue to explore novel coatings and improve existing ones. The future directions for foul-release and antifouling coating research describe below are not meant to be comprehensive. Rather, they are intended to highlight a few of the general topics that deserve additional attention.

Foul-release Coatings for Marine Applications

The continued global trend towards more stringent environmental regulations fuels the development of nontoxic coating systems. Because the market for antifouling coatings is so large in marine applications most current coating research continues to focus on marine fouling. Coating researchers have difficulty securing funding for antifouling research in freshwater (D. Webster, pers. com.), and it is unclear how the efficacy of coatings developed for marine organisms and habitats would change in freshwater.

High-throughput Combinatorial Assays

High-throughput combinatorial assays allow multiple parameters to be rapidly evaluated. These methods are quickly identifying optimal coating formulations (e.g. the type, quantity and mixing time for catalysts and solvents). For example, combinatorial methods identified eight crosslinked siloxane-polyurethane coatings out of 288 that appear promising and warrant further characterization (Ekin et al. 2007). It is still difficult, however, to correlate molecular level parameters evaluated under high-throughput combinational assays with antifouling performance under natural conditions.

Improving Durability of Foul-Release Coatings

Research is currently focused on improving the mechanical weakness of hydrophobic topcoats such as PDMS. The topcoat of coatings that rely on a non-polar, low surface free energy, and elasticity to resist macrofouling, such as hydrophobic silicone-based and fluoropolymer-based coatings, is susceptible to abrasion and delamination. Different topcoats are being explored to address this. PDMS coatings are filled with small, self-assembling cylinders or crystals (~10 nm wide x 5 μm long), which are synthetic multi-wall carbon nanotubes (NT) and natural sepiolite (NS) (Grozea and Walker 2009). Some results suggest that

NT- and NS-filled PDMS have increased stiffness (increased tensile modulus) and increased release properties compared to unfilled PDMS (Grozea and Walker 2009).

Research is currently underway to address problems due to silicone delamination from underlying substrates. Efforts are focused on developing a self-stratified, crosslinked topcoat composed of silicone mixed with polyurethane polymers (Krishnan et al. 2008). The two components of the topcoat are bonded (i.e., the amine groups of 3-aminopropyl-terminated PDMS bonded to isocyanate crosslinker). During the curing process, the silicone component migrates to the surface while the polyurethane component remains internal due to differences in surface energy (Majumdar et al. 2007a). This allows the polyurethane component to form stronger bonds with the anticorrosive epoxy primer, and the silicone provides the foul-release properties at the coating surface (Ekin and Webster 2007). Several siloxane-urethane coatings that are cured for 5 to 7 hours had significantly lower barnacle adhesion strengths compared to Intersleek, which was a fluoropolymer-tie coat-epoxy system (Majumdar et al. 2007b). A fluorinated polyurethane coating that combines the durability of polyurethanes with the low surface energy of fluoropolymers limited attachment and adhesion strength of marine barnacles, bryozoans, and algae during a four-month, *in situ* panel experiment. This polymer fouled slowly, cleaned easily, and was durable in marine waters for four months (Brady and Aronson 2003).

Hybrid Coatings

Hydrophobic and hydrophilic fractions are being combined to make amphiphilic surfaces, which could improve coating performance across an array of species. Coating performance depends on many parameters including the type of fouling organism. For example, hydrophilic polymers are usually more effective against microfouling while hydrophobic polymers are more effective against macrofouling (Grozea and Walker 2009; Krishnan et al. 2009). Hydrophilic PEG fractions combined with hydrophobic fluoroalkyl parts make a copolymer that is effective against both *Navicula* diatoms and *Ulva* zoospores (Grozea and Walker 2009; Krishnan et al. 2009). Broader spectrum antifouling activity is possible with increased heterogeneity of the coating composition and morphology in a hyperbranched fluoropolymer (HBFP)-PEG coating. The HBEF-PEG coatings deter protein adhesion similar to PEG polymers, and have foul-release properties with *Ulva* zoospores similar to low surface energy fluoropolymers (Gupipati et al. 2005).

Resistance to initial settlement is being improved for foul-release coating by bonding biocides to the PDMS matrix. Fouling can develop on foul-release coatings in low-flow conditions. Bonding biocides onto the PDMS matrix could improve both antifouling and foul-release properties. For example, quaternary ammonium salt moieties can be bound to silicone surfaces with different topographic features (Gibson 2002; Grozea and Walker 2009) Thomas et al. (2007) reported that when the biocide Triclosan was covalently bonded to a silicone polymer significant reductions in macrofouling of panels occurred in marine waters showed.

Less toxic biocides are being investigated to replace the heavy metals used in many antifouling coatings. Antifouling coatings based on zinc peroxide showed similar leaching and polishing rates compared to cuprous oxide-based coatings, and an ablative copolymer containing zinc peroxide provided better antifoulant protection compared to a similar copolymer with zinc oxide (Olsen et al. 2009). Microencapsulation has also been explored as a means to incorporate less toxic biocides into coatings (Chambers et al. 2006; Haslbeck 2007). Microencapsulation of biocides could extend coating lifespan and environmental compliancy by increasing the biocide loading capacity of coatings while reducing the biocide release rates. When the biocide 4,5-dichloro-2-n-octyl-4-isothiazolin-3-one (DCOIT) was incorporated into the antifouling coating of the Jotun A/S ablative copper system the panels were free of macrofouling for one year in static, marine water. Microencapsulated panels were more effective against microfouling than ablative copper coated panels without the microencapsulated DCOIT (Haslbeck 2007).

Biomimicry

Natural antifoulant compounds and surfaces are being explored and incorporated into coatings. Cannabinoids such as anandamide had antifouling properties against *D. polymorpha* in 48-hour exposure experiments. Anandamide prevented the byssal formation in *D. polymorpha*, without producing toxic effects upon the mussels (Angarano et al. 2009). Extracts of *Pseudomonas* sp., particularly the bacterial strain NUDMB50-11, incorporated into paints demonstrated excellent antifouling performance against bacteria, *Balanus amphitrite* barnacle cyprid, and *Ulva lactuca* algal zoospores (Burgess et al. 2003; Chambers et al. 2006; Dobretsov et al. 2009). Halogenated furanones extracted from red algae are effective antifoulants (López et al. 2006). Sodium benzoate and tannates from chestnut, mimosa, and quebracho produce a narcotic effect on nauplii of *B. amphitrite* when incorporated into a soluble matrix antifouling coating and reduced settlement during a four-month panel experiment in marine waters (Stupak

et al. 2003). Dobretsov et al. (2009) reviewed antilarval compounds derived from marine bacteria and identified several compounds that inhibited the settlement and attachment of *B. amphitrite* including, ubiquinone from *Alteromonas* sp.; 6-bromoindole-3-carbaldehyde from *Acinetobacter* sp.; phenazine-carboxylic acid, hydroxyphenazine, heptylquinol-one, and nonylquinol-one from *Pseudomonas* sp.; and unknown exopolysaccharides, polymers and other substances from *Halomonas marina*, *Vibrio campbelli*, *Micrococcus* sp. and *Rhodovulum* sp.

Micro-textured Surfaces

Micro-engineered surface topographies incorporated on the traditionally smooth surface of foul-release coatings can enhance antifouling and foul-release properties. There is a critical, maximum size for surface topography that enhances antifoulant properties, but this critical size differs among fouling organisms (Hoipkemeier-Wilson et al. 2004). Multi-level hierarchical patterning could produce surface topographies at many scales, which would provide broad spectrum antifoulant protection. Polyester, polyamide, nylon, or polyacryl fiber flock coatings made by adhering electrostatically charged fibers perpendicular to the coating surface appear promising against barnacles (Chambers et al. 2006).

Conclusions

There are problems with all commercially available coatings used to mitigate macrofouling in RWS. Foul-release coatings are mechanically weak, strong and protective coatings are not effective against macrofouling, antifouling coatings release biocides, are expensive, and have an effective lifespan of only five to seven years in panel/grate experiments and trial applications.

The commercially available coatings that are identified as candidates for immediate application on CRB facility components are Bioclean SPGH (Chugoku Marine Paints), Smart Surfaces (Fuji Hunt Smart Surfaces), and Intersleek 900 system (International Marine Coatings). These three foul-release coatings have excellent antifouling and foul-release properties against freshwater macrofouling, are nontoxic, and have effective lifespans greater than five years. These coatings are soft, however, and are susceptible to damage from gouging, scraping and delamination.

Foul-release coatings are good candidates for facility components such as intake tunnels, intake bays, trash racks, intake wells, cell blocks, service water pumps, pump columns, traveling

screen housing, screens and strainers, circulating water piping, service water piping, and condenser water boxes. Foul-release coatings are best utilized on external facility components due to the lack of biocides, and the potential for coating delamination and the clogging of downstream components.

Several commercially available copper-based coatings deserve further investigation. Leached copper ions are an effective biocide against freshwater macrofouling. Copper-based antifouling coatings that deserve further investigation included copper metal, LuminOre (copper cold-spray), brass metal, bronze metal, and Epco-Tek 2000 (copper powder incorporated into epoxy). Copper and copper alloy metals, LuminOre, and Epco-Tek 2000 have excellent antifouling performance against freshwater macrofouling for at least 15 months, are durable, and are expected to have effective lifespans beyond five years. The environmental compliancy of these coatings will be constrained by copper leaching rates.

Zinc galvanizing also deserves further consideration. Zinc galvanizing is not completely effective against freshwater macrofouling, and appears to be less effective in areas with flow. Zinc galvanizing, however, offers some macrofouling control, is commonly used for galvanic corrosion protection, and is cheaper than other coatings. Zinc galvanizing is exempt from FIFRA registration when marketed for corrosion protection, and the typical release rates of 5 $\mu g/cm^2/$ day are compliant in most waters.

The potentially poor environmental effect of antifouling coatings is based on their release of heavy metals. Estimation of how bulk water concentrations, which are the basis for regulation of heavy metals, would be impacted by leaching from antifouling coatings on RWS in the CRB is required. Additionally, the review of regulations pertaining to the use of biocides might identify products that could legally be used in CRB facilities. Specific information about the coatings was often not readily provided (e.g. name of biocide and leach rates) and this complicated the assessment of environmental compliance.

Antifouling metals applied as pure metal or thermal-spray including copper, bronze, and to a lesser extent brass, are good candidates for application to high value components like fire protection systems, and condenser boxes. Copper piping or copper inserts are good candidates for embedded, small diameter (< 20 cm) piping, such as the piping supplying water to oil coolers and local air conditioners. Copper powder mixed into epoxy or polyester resin are good candidates for concrete structures such as intake tunnels and intake bays as well as trash racks,

medium sized piping, raw water heat exchanger water boxes, condenser boxes, screens and strainers.

New coatings are being developed but this process is lengthy and expensive. Most current coating research is focused on marine fouling because of the size of the market and sources of available funding (e.g. US Navy). It is unclear when new coatings will be commercially available.

Selection of specific coating materials is dependent on a number of factors. Most commercially available coatings could be applied to concrete and steel, and so the limiting factors are component accessibility, flow patterns, component value, and environmental regulation. Coatings are not applicable to many RWS components due to the small size and limited access. In general, a component must be large enough to accommodate an adult human for application of the coating and the surface must be completely dry prior to coating application. Metals like copper could accelerate corrosion of certain substrates such as carbon steel, and steps are required to protect the bare substrate. Flow patterns affect the location and severity of macrofouling, and the efficacy of the coatings. Intakes tend to be more heavily fouled than components more distant from the raw water source and may require more frequent recoating. Macrofouling is generally most problematic in flow velocities less than 2.0 m/s. Foul-release coating wear away quickly at flow velocities greater than 3.0 m s, and perform best in flow velocities ranging from 0.9 to 2.0 m/s. High flow velocities increase the leaching rate rate of biocides from antifouling coatings, which decreases efficacy and lifespan.

In general, there is a paucity of long-term evaluation on coating lifespan, durability and performance. Coating manufacturers are very protective of proprietary information. Private agreements between coating manufacturers and power/drinking water plants curtailed our access to existing long-term data collected during small and large-scale trial applications at these facilities.

Coatings may not be necessary in all CRB facilities. Calcium concentrations required for growth and water flow velocities may limit fouling by dreissenid mussels, should they be introduced to the CRB. The magnitude of macrofouling is typically site specific and varies by location and season. USACE facilities located in Midwest and Northeast US do not apply coatings on a large scale to mitigate macrofouling on external structures (trash racks, intake bays,

and intake tunnels). Chlorine injections and periodic removal (e.g. hydro-lazing) mitigate macrofouling in these facilities.

Recommendations

1. Do not apply existing commercially available coatings in CRB facilities at this time. There are problems with all currently available coatings and research will continue to increase the effectiveness of coatings. The USBOR is currently dealing with severe macrofouling at its facilities on the lower Colorado River, and valuable insight will be gained from their experiences. Reactive control efforts maintained facility operations and safety in other North American facilities that are colonized by these mussels.

2. BPA and other stakeholders should begin panel experiments using the following coatings: Bioclean SPGH (Chugoku Marine Paints), Smart Surfaces (Fuji Hunt Smart Surfaces), Intersleek 900 (International Marine Paints), Epco-Tek 2000 (Hi Tek Coatings Co.), LuminOre (LuminOre), and thermal sprays of copper and its alloys. Studies indicate that these coatings are effective at preventing fouling by dreissenid mussels. The objective of the recommended panel experiments is to evaluate the lifespan and durability of these coatings in the water chemistry environment in the CRB. Panels could be deployed in the CRB for varying time periods and then transported to dreissenid mussel-infested waters for efficacy testing. Foul-release coatings could be evaluated visually. Chugoku Marine Paints, EPaint, and LuminOre indicated a willingness to provide test panels for field evaluations of their products.

3. Federal and state regulations pertaining to the use of antifouling coatings and their biocides within the CRB needs to be explored further. Heavy metal and thermal spray based coatings are effective, durable, and cheaper than foul-release coatings. Epco-Tek 2000, an epoxy with embedded copper powder, is also effective, durable and is expected to have a long lifespan.

4. The results from ongoing publicly and privately funded research to identify effective commercially available coatings must be reviewed when the studies are completed. Panel and grate experiments conducted in the lower Colorado River by USBOR and MWD are assessing the performance of many commercially available foul-release, thermal-spray, and protective coatings against *D. bugensis*. Arrangements should be made with Dr. Allen Skaja (USBOR) to receive copies of the USBOR reports and with Phil Drooks (MWD) to discuss results of these studies.

5. BPA and other CRB stakeholders should explore the options to gain access to existing long-term data that was unavailable for this report due to confidentiality agreements. Short- and long-term evaluations of coatings have been completed by MWD, EPRI, Ontario Hydro, American Power and many other water and power facilities in North America; however, access to these data is restricted by confidentiality agreements. In cases where reports are published or provided, the coating names and manufacturers are often not listed (e.g. EPRI, Ontario Hydro).

6. Efforts to prevent the introduction of freshwater fouling mussels into the CRB should be increased. Preventive efforts are cheaper than reactive control efforts and a delay in the arrival of dreissenid mussels may permit time for development of more effective and less expensive new coatings. Prevention efforts should focus on overland transport from the Eastern and Southwestern U.S. and ballast water. Species of concern include *Dreissena polymorpha, D. bugensis*, *L. fortunei,* and *M. leucophaeata.*

7. Early detection efforts within the CRB should be increased. The dependence of CRB hydropower facilities on once-through raw water for heat exchangers via concrete-embedded piping makes these facilities particularly vulnerable to freshwater macrofouling. Some CRB habitat is likely suitable for these mussels, and high population densities may occur soon after introduction. It is important to quickly implement control efforts upon the first discovery of veligers or adults and to limit spread of a new infestation.

8. The suitability of the CRB habitat to these mussels needs to be further investigated in order to predict the extent of macrofouling should they become established. Ongoing growth-rate and survivorship studies that focus on dissolved calcium will allow better predictions of the magnitude of fouling throughout the CRB. Other environmental factors that should be studied include water temperature, flow, food quality, and food quantity.

9. Phillips et al. (2005) estimated increased maintenance costs for hydropower facilities in the CRB that could be expected if dreissenid mussels were introduced. A more detailed cost analysis should be conducted. A major deterrent to the use of coatings is the initial application costs associated with labor and materials, but these costs may be offset by reductions in maintenance and disposal costs over the lifespan of the coating versus other control options such as hydro lazing/water jet blasting. Existing maintenance costs should be itemized, and other facilities that have experienced freshwater macrofouling should be contacted to determine changes in maintenance operations and costs in order to predict expected changes following an establishment of one of these mussel populations within the CRB.

10. Several promising coatings lack performance data. These coatings should be evaluated in more detail. Promising coatings to investigate further included Sylgard 184 (Dow Coming Corp), Mille light (Hempel), Micron Eco (International), SSC-44 (US Gloss), SeaLion (Jotun Group), Lefant H2000 (Lotréc AB), Hempasil X3 (Hempel), ECOLOSILK (Nippon Paint), SigmaGlide (Sigma Coatings), Sigma LSE (Sigma Coatings), and Nipple Sleek (Nippon).

11. The development of new coatings targeting freshwater macrofouling needs to be supported and funded. Marine macrofouling is the market driver for antifouling coating development and most funding for independent analysis of coating performance is conducted in marine systems. Research should determine if efficacy studies done on coatings in marine systems are applicable to freshwater.

Appendix I. Biology of Freshwater Mussels of Concern

Growth and survival

Adult *D. polymorpha* and *D. bugensis* are typically 10 to 30 mm in length with a maximum shell length between 36 to 46 mm (Mills et al. 1993; Karatayev et al. 2007). The shell length for planktonic *D. polymorpha* and *D. bugensis* veligers ranges from 70 to 350 μm and 40 to 300 μm, respectively (Ackerman et al. 1994; Nichols and Black 1994). *L. fortunei* adults are typically 20 to 30 mm in length but can reach a shell length of 42 mm (Karatayev et al. 2007). *M. leucophaeata* adults are typically between 10 to 20 mm in shell length, with most measuring greater than 10 mm (Laine et al. 2006). The maximum size for *M. leucophaeata* adults ranges between 21 and 25 mm (Laine et al. 2006; Siddall 1980).

Macrofouling mussels are highly fecund. An individual *D. polymorpha* female can release 275,000 to 1.5 million eggs/ year (Karatayev et al. 2007; Nichols 1996). The density of newly settled *D. polymorpha* can be as high as 700,000 individuals/ m^2 in one growing season, and adult mussel beds reach densities greater than 200,000 individuals/ m^2 (Jenner et al. 1998). Populations of *L. fortunei* mussels range from 45,000 to 150,000 individuals/m^2 (Cataldo and Boltovskoy 2000; Magara et al. 2001; Marońas et al. 2003). In Europe, *M. leucophaeata* veliger densities reach 15,000 veligers/m^3 (Laine et al. 2006) newly settled *M. leucophaeata* in Europe can be as high as 6.5 million individuals/ m^2 (Rajagopal et al. 2002). Densities of adult *M. leucophaeata*, however, are typically around 28,000 individuals/ m^2 (Laine et al. 2006).

D. polymorpha populations fluctuate. *D. polymorpha* population density depends on the time since establishment, the availability of suitable substrates, lake morphometry, and trophic status (Burlakova et al. 2006). The maximum population density for *D. polymorpha* usually occurs two to three years after the population is large enough to detect (Burlakova et al. 2006). It is often difficult to determine the time of initial introduction, but *D. polymorpha* and *D. bugensis* quickly reach high densities. For example, *D. polymorpha* densities on a Detroit Edison intake went from 200 mussels/m^2 in 1988 to 200,000 mussels/ m^2 in 1989 (Miller et al. 1992). *D. bugensis* are found 21 miles into Metropolitan Water District's Colorado River Aqueduct at densities between 2 to 10 mussels/ m^2 in March of 2007, and another inspection four months later showed penetration 125 miles at densities up to 500 mussels/ m^2 (R. DeLeon, pers. com.).

Fouling mussels grow fast and quickly reach sexual maturity. Mackie (1993) reported that the mean growth rate was 0.13 mm/ day for small, adult *D. polymorpha* and 0.05 mm/ day

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for 15-mm adults; annual growth was 15 to 20 mm. MacIsaac (1994) found that the mean growth rate was 0.12 mm/ day for small, adult *D. bugensis* and 0.04 mm/ day for 15-mm adults. *D. polymorpha* in the Great Lakes reach sexual maturity in 8 to 10 months when shell lengths are 5 to 10 mm (Mackie 1993; Mackie and Schloesser 1996; Nichols 1996). The time required for *D. bugensis* to reach sexual maturity in North America is unknown. *L. fortunei* grows 15 mm/ year (Magara et al. 2001), and reaches sexually maturity in three to four months (Karatayev et al. 2007). *M. leucophaeata* grows about 0.03 mm/ day (Laine et al. 2006), and can reach 14 to 17 mm shell length by the end of the first growing season (Jenner et al. 1998; Laine et al. 2006). *M. leucophaeata* reached sexual maturity in about two months when most shell lengths are greater than 7 mm (Jenner et al. 1998). The minimum shell length for sexually mature *M. leucophaeata* iss 2.4 mm (Jenner et al. 1998).

D. polymorpha and *D. bugensis* growth rates depend on water temperature, quality and quantity of food, and age class. Growth rates for both species are higher in young mussels (Mackie 1993; Mackie and Schloesser 1996; Thorp et al. 2002), at high food concentrations (up to 2 mg C/L), and water temperatures between 10° to 15^oC (MacIsaac 1994; Mackie and Schloesser 1996). Baldwin et al. (2002) found that *D. bugensis* equaled or exceeded *D. polymorpha* growth rates at 6° and 23^oC and had superior growth at lower food concentrations.

Macrofouling mussels have a short lifespan compared to freshwater unionaceans. Some species of unionacea mussels in North America live over 100 years (McMahon 1991). *D. polymorpha* in the Great Lakes live 1.5 to 7 years with most living two years (Mackie 1993; Mackie and Schloesser 1996; McMahon 1991). The lifespan of *D. bugensis* in North America is unknown. *L. fortunei* have a lifespan of 1 to 5 years outside their native range (Magara et al. 2001; Marońas et al. 2003), with most living between two years (Magara et al. 2001). *L. fortunei* in China, however, live up to 10 years (Marońas et al. 2003). *M. leucophaeata* has a lifespan of 3 to 5 years (Therriault et al. 2004). A significant proportion of the damage in raw water systems caused by *D. polymorpha, D. bugensis, L. fortunei* and *M. leucophaeata* is due to the dead and detached mussels that clog constricted areas (Jenner et al. 1998; Magara et al. 2001; Neitzel et al. 1984).

D. polymorpha, D. bugensis, L. fortunei, and *M. leucophaeata* are efficient filter-feeders that remove particles from the water column and concentrate debris and energy in the benthos. *D. polymorpha* select food particles from 0.4 to 750 μm (Karatayev et al. 2007). The filtration

rate varies with environmental parameters, and the condition of the mussels. Filtration rates increase with increasing water temperature and mussel size (Diggins 2001; Karatayev et al. 2007; Rajagopal et al. 2005), as well as other parameters such as flow velocity (Ackerman 1999), and season of collection (Diggins 2001). Filtration rates in *D. polymorpha* and *D. bugensis* are similar at sizes between 10 mm and 15 mm (Ackerman 1999; Baldwin et al. 2002; Diggins 2001); 18 to 402 mL per hour per mussel (Ackerman 1999; Baldwin et al. 2002; Diggins 2001; Karatavey et al. 2007). *D. bugensis* mussels 20 mm in length, however, have higher filtration rates compared to the same size *D. polymorpha* mussels (Ackerman 1999; Diggins 2001). The filtration rate of *L. fortunei* ranges between 125 to 350 mL per hour per mussel (Sylvester et al. 2005). The maximum filtration rate for 20-mm *M. leucophaeata* mussel is 55 mL per hour per mussel (Rajagopal et al. 2005).

These mussels produce planktonic larvae (veligers) that disperse throughout hydrologic connected waterways and facility components. They mass spawn and release gametes into the water column for external fertilization. Other freshwater mussels, such as *Corbicula* spp. or unionacea mussels, produce veligers that disperse by crawling on the substrate or attaching to the gills of fish (McMahon 1991; Naimo 1995).

Veligers are more vulnerable than adult mussels and experience high mortality. Most veliger mortality (99%) occurs in the settlement and metamorphosis stage (Mackie and Schloesser 1996; Nichols 1996; Sprung 1993). High mortality rates also occur in the D-shaped larval stage (Sprung 1989). Metamorphosis is physiologically expensive as mussels stop feeding, realign internal body structures, and alter shell growth patterns (Nichols 1996). Sources of veliger mortality include physical damage (e.g. shear stress) (Horvath and Lamberti 1997); bacterial infection; shortage of food; and predation by fish larvae, small fish (10-16 mm), zooplankton (e.g. *Daphnia*), and adult mussels (Sprung 1989; Sprung 1993). *D. polymorpha, D. bugensis*, *L. fortunei*, and *M. leucophaeata* veliger salinity and temperature tolerances increase with larval age (Karatayev et al. 2007; Rajagopal et al. 2005; Sprung 1993; Verween et al. 2007; Wright et al. 1996).

Macrofouling mussels attach to solid substrates using byssal threads in freshwater environments. Macrofouling via byssal attachment is generally restricted to brackish and marine environments; most freshwater mussels bury into soft sediment using the foot (McMahon 1991). The *D. polymorpha* byssus apparatus is a bundle of proteinaceous threads attached to the

retractor muscles of the mussel foot (Eckroat et al. 1993; Rzepecki and Waite 1993). The byssal threads attach to the substrate using adhesive plaques.

A number of factors influence the location of attachment and attachment strength. Byssal thread formation is related to mussel size, mechanical agitation of the water, water chemistry, water temperature, and the substrate (Eckroat et al. 1993). Thread formation increases with mussel size (Ackerman et al. 1993; Eckroat et al. 1993). Thread formation and attachment strength increase with water velocity and turbulence to a threshold level and then is inhibited (Lachance et al. 2008; Rzepecki and Waite 1993). *M. edulis* thread production is positively related to water temperature from 0° to 25^oC; it is inhibited above 26^oC (Lachance et al. 2008). Attachment strength of cultured *M. edulis* decreases immediately following spawning (Lachance et al. 2008). *D. polymorpha* adhesion strength varies with substrate type, but the causal mechanisms are unclear (Ackerman et al. 1992; Ackerman et al. 1996). Attachment strength increases with substrate surface roughness (Ackerman et al. 1999; Marsden and Lansky 2000), which is logical in that greater surface roughness allowed greater penetration of mussel adhesive. Matsui et al. (2002), however, reported that the strength of *L. fortunei* byssal attachment was not significantly affected by substrate surface roughness. Other substrate surface properties like the surface free energy and elastic modulus also affect the strength of byssal attachment (Vladkova 2009), but the relationship between adhesion strength and surface free energy is not linear (Brady and Singer 2000).

These mussels inhabit freshwaters but they vary in salinity tolerances. Salinity tolerances are influenced by temperature, sodium and potassium concentrations, and rate of acclimation (Mackie and Schloesser 1996). Adult *D. polymorpha* mussels are found in North America at salinities up to 12‰ at 20^oC (Mackie and Schloesser 1996; Orlova et al. 2005), but most *D. polymorpha* populations are found between 0 to 4‰ (McMahon 1996). *D. bugensis* is less tolerant to salinity, and inhabits systems ranging from 0 to 4‰ in North America (Orlova et al. 2005). *D. bugensis* in Europe tolerates salinity up to 8‰ (Orlova et al. 2005). *L. fortunei* is more tolerant of salinity than *D. polymorpha*, and *D. bugensis*, with an upper salinity limit of 14 to 15‰ (Boltovskoy et al. 2006; Karatayev et al. 2007). *M. leucophaeata* had the broadest salinity tolerance of all these mussels, inhabiting European waters ranging from 0‰ (Laine et al. 2006) to 32‰ (Montalto and Drago 2003; Verween et al. 2007). The optimal and normal salinity range for *M. leucophaeata* is 1.38 to 12.66‰, and 0.21 to 18.08‰, respectively (McNeill 1992).

Salinity tolerances change with life stage. Embryonic development occurs in North America at salinities between 0 and 6‰ at 20°C *in D. polymorpha,* and between 0 and 4‰ in *D. bugensis* (Orlova et al. 2005). *D. polymorpha* and *D. bugensis* veligers can survive in salinities between 0 and 2‰ (Wright et al. 1996) and *D. polymorpha* veligers survived up to 10‰ (Nichols 1996). *M. leucophaeata* salinity tolerance for larval development was slightly lower than for adults. Larval development in Europe occurred at salinities ranging from 3 to 32‰ (Montalto and Drago 2003; Verween et al. 2007).

Dissolved calcium concentration influences the mussel distribution and abundance. Most (~80%) of the calcium deposit in the *D. polymorpha* shell is actively taken up from the water (Hincks and Mackie 1997), but both *D. polymorpha* and *D. bugensis* also obtain calcium from food (Nichols 1996). Veligers of *D. polymorpha* in Europe, have a 3% survival rate in 12 mg Ca^{2+}/L and between 20 and 25% survival in calcium concentrations greater than 47 mg/ L (Sprung 1987). North American *D. polymorpha* juveniles show initial growth at calcium concentrations between 8.5 and 11 mg Ca^{2+}/L (Hincks and Mackie 1997; McMahon 1996) and moderate shell growth between 25 and 26 mg Ca^{2+}/L (McMahon 1996). In general, *D. polymorpha* adults inhabit waters with calcium concentrations greater than or equal to 15 mg Ca^{2+}/L and populations became dense at concentrations greater than or equal to 21 mg Ca^{2+}/L (McMahon 1996). *L. fortunei* has broader tolerances to calcium than *D. polymorpha* (Karatayev et al. 2007). *L. fortunei* dwells in South America waters with calcium concentrations as low as 3 mg/L, and forms dense populations in water with 3 to 9 mg/L dissolved calcium (Boltovskoy et al. 2006).

The pH influences mussel distribution and abundance as well. dreissenid mussel growth is generally limited at pH concentrations above 10, and *D. polymorpha* loses calcium to the external environment at pH concentrations less than 6.5 to 6.9 (Hincks and Mackie 1997; McMahon 1996). *D. polymorpha* gamete development occurs between pH 7.4 and 9.4, and is optimal at pH 8.5 (Sprung 1993). *D. polymorpha* veligers are found in North America at pHs between 7.4 and 9.4; pH 8.4 is optimal (McMahon 1996). The lower pH limit for *L. fortunei* adults is 5.5 (Boltovskoy et al. 2006).

Reproduction and juvenile development

Understanding the factors that influence the start, duration and peak of gametogensis, spawning, and settlement permits targeted management of all life stages. Gametogensis and spawning are physiologically expensive for adults. *D. polymorpha* adult total body weight and gonad volume are significantly reduced (30-50%) following gametogensis and spawning (Garton and Haag 1993; Nichols 1996; Ram et al. 1996). Veligers are the life stage that is most vulnerable to management activities. Smaller mussels are more vulnerable to most types of management (e.g. chemical, desiccation) than larger mussels (Karatayev et al. 2007; McMahon 1996; Montalto and Drago 2003).

Gametogenesis is influenced by the physical and chemical characteristics of the habitat. Low temperatures delay or prevent the onset of sexual maturity in *D. polymorpha* (Roe and MacIsaac 1997); gametogenesis does not occur below 9°C (Claxton and Mackie 1998). *D. polymorpha* gonad volume increases throughout the winter and peaks between May and June at temperatures between 12° and 24°C, and is optimal at 18°C in North America (Ram et al. 1996; Claxton and Mackie 1998; Sprung 1993; Roe and MacIsaac 1997). *D. bugensis* has a lower thermal limit for gametogensis than *D. polymorpha* (Roe and MacIsaac 1997). *D. polymorpha* gamete development is affected by pH and calcium concentrations (Sprung 1993). For example, calcium concentrations less than 40 to 60 mg Ca^{2+}/ L increase the number of crippled gametes in European *D. polymorpha* populations (Sprung 1993). Gametogensis in *L. fortunei* is also temperature dependent (Darrigran et al. 2003b). *L. fortunei* gametes are present in adults nearly year-round (Darrigran et al. 1999; Darrigran et al. 2003). *M. leucophaeata* gametogensis begins at water temperatures around 13°C (Laine et al. 2006), but is more abundant at greater than 15°C (Verween et al. 2007). Optimal temperature for *M. leucophaeata* gamete development is 22 ± 2°C, and normal gamete development occurs at salinities between 3 to 22‰ (Verween et al. 2007).

It was difficult to predict the timing and magnitude of gametogensis. *D. polymorpha, D. bugensis*, and *L. fortunei* mussels carry ripe and developing gametes for a long time (Darrigran et al. 1999; Darrigran et al. 2003; Nichols 1996). Each mussel produces multiple cohorts (Darrigran et al. 1999; Darrigran et al. 2003; Ram et al. 1996).

The environmental factors that influence spawning vary among species and populations. Water temperature and the presence of gametes in the water appear to stimulate *D. polymorpha*

and *D. bugensis* spawning (Marsden 1992; Nichols 1996; Ram et al. 1996). Garton and Haag (1993), however, reported that *D. polymorpha* spawning was not correlated with temperature, and Claxton and Mackie (1998) and Nichols (1996) found considerable geographic and seasonal variation in the temperature that *D. polymorpha* spawned. Spawning in *L. fortunei* is a function of water temperature (Cataldo and Boltovskoy 2000; Darrigran et al. 2003; Marońas et al. 2003), and *M. leucophaeta* spawning is influenced by water temperature and salinity (Verween et al. 2005). Other factors that can influence spawning in *D. polymorpha* and *D. bugensis* include phytoplankton abundance and/or quality, neighboring adult mussel density, influx of larvae from disjunct populations, and photoperiod (Garton and Haag 1993; Ram et al. 1996).

The beginning of spawning is water temperature dependent, but differs between populations. Generially, *D. bugensis* begins spawning at 9^oC, and *D. polymorpha* begins spawning at 12^oC. In North America, however, *D. polymorpha* spawning usually begins at temperatures greater than 18^oC (Adrian et al. 1994a; Claxton and Mackie 1998; Garton and Haag 1993; Mackie 1993; McMahon 1996; Nichols 1996). *D. polymorpha* veligers first appear in May and June in North America (Garton and Haag 1993; Kraft et al. 1996; Mackie 1993; Nichols 1996; Sprung 1989; Thorp et al. 1994). *L. fortunei* spawning in South America begins in September when water temperatures are greater than 16° to 17^oC (Cataldo and Boltovskoy 2000; Darrigran et al. 2004). *M. leucophaeata* usually begins to spawn in Europe when water temperatures are between 15° and 20^oC (Verween et al. 2005; Verween et al. 2007) and the salinity is between 2.6 and 4.9‰ (Verween et al. 2005).

The timing and magnitude of peak spawning varies between years, locations and species. *D. polymorpha* and *D. bugensis* are sequential spawners (Ackerman et al. 1993; Nichols 1996; Sprung 1993); peaks in veliger abundance in the Great Lakes are generally bimodal but may also occur once per year (Garton and Haag 1993) or year-round (Nichols 1996). Annual variation in spawning magnitude can be large, and is sometimes inversely related to adult mussel abundance (Keppner et al. 1996). *D. polymorpha* veliger densities in the Ohio River increased from less than 100/ m^3 in 1994 to 8,000/m^3 in 1995. A similar progression was seen in the upper Mississippi River with less than 100/m^3 found in 1993 compared to 2,000 to 7,000/m^3 in 1994 (Keppner et al. 1996). Veliger densities in the Niagra River changed from a short duration, high magnitude event in 1991 to an extended, moderate magnitude event in 1995 (Keppner et al.

1996). Similarly, *L. fortunei* has multiple major and minor spawning events in South America (Cataldo and Boltovskoy 2000; Darrigran et al. 2003)

The timing of peak veliger abundance appears to coincide with peak summer water temperatures. Peak *D. polymorpha* veliger abundance typically occurs between July and August in the Midwest and Northeast U.S. (Adrian et al. 1994, Garton and Haag 1993; Keppner et al. 1996; Kraft et al. 1996), when water temperatures are between 16° and 19^oC (McMahon 1996). *L. fortunei* veliger density peaks in South America between December and May (Darrigran et al. 2003; Darrigran et al. 2004). Peak *M. leucophaeata* veliger densities occur in Europe between July and September when water temperatures are around 21^oC and salinity from 3.9 to 10.3‰ (Verween et al. 2005).

The time period veligers are present in the water column is quite variable. *D. polymorpha* and *D. bugensis* spawning may be highly synchronized and occur over a few days or less synchronized and occur over several weeks (Adrian et al. 1994; Garton and Haag 1993; Nichols 1996; Ram et al. 1996). *D. polymorpha* veligers are present in European systems between 3 to 8 months (Karatayev et al. 2007; Sprung 1993), and in North America 8 to 10 months (McMahon and Bogan 2001). *L. fortunei* veligers are present for 8 months in Europe (Karatayev et al. 2007), and between 2 to 9 months in South America (Cataldo and Boltovskoy 2000; Darrigran et al. 2004). In South America, it appeared that spawning was continuous between September and May, with very low densities found during the winter period between June and August (Cataldo and Boltovskoy 2000). *L. fortunei* veligers are present in Japan from May to September (Magara et al. 2001). *M. leucophaeata* veligers in Europe are present between May to October (Rajagopal et al. 2005; Verween et al. 2007). *M. leucophaeata* spawning in North America occurs later in the year than in European populations (Verween et al. 2005).

The duration of the planktonic larval period is determined by the rate of veliger development. *D. polymorpha* veligers grows between 1.0 and 24 μm/day and the time required for *D. polymorpha* to go from the D-shaped to the plantigrade larval stage varies from 8 to 240 days. *D. polymorpha* and *D. bugensis* veligers may overwintered in the water column (Nichols 1996; Sprung 1993). In South America, *L. fortunei* veligers are generally in the D-shaped larval stage for 1 to 2 days and the umbonal larval stage for 8 to 9 days (Cataldo and Boltovskoy 2000).

Veliger development is primarily a function of temperature and food availability (Mackie and Scloesser 1996; Nichols 1996; Sprung 1989). *D. polymorpha* veliger development occurs

between 12° and 24^oC, 17° to 18^oC is the optimal temperature (McMahon 1996). *D. polymorpha* and *D. bugensis* veligers can survive temperatures between 0° and 30^oC (Nichols 1996; Sprung 1993). *L. fortunei* and *M. leucophaeata* veligers are present when water temperatures are greater than 20^oC in Japan (Magara et al. 2001; Darrigran et al. 2004; Jenner et al. 1998).

Settlement

Settlement is an active process that involves initial settlement, metamorphosis, and translocation. *D. polymorpha* and *D. bugensis* appear not to discriminate surfaces on which they initially settle (Sprung 1993), although *D. bugensis* pediveligers settle and metamorphosize slower than *D. polymorpha* (Wright et al. 1996). After completing metamorphosis, *D. polymorpha* and *D. bugensis* mussels move to preferred substrates such as the undersides of objects (Ackerman et al. 1994; Sprung 1993). *D. polymorpha* and *D. bugensis* settlement and recruitment is reduced in water column calcium concentrations less than 50 mg/L (Sprung 1993), oxygen concentrations less than 2.0 mg/ L (R. DeLeon, pers. com.), water velocities greater than 1.8 m/ s (Claudi and Mackie 1994), unsuitable substrates, and large amounts of sediment (Sprung 1993). Juvenile and adult *D. polymorpha* and *D. bugensis* translocate year-round (Claudi and Mackie 1994), although smaller mussels are more mobile (Eckroat et al. 1993). Karatayev et al. (2007) indicate that only young *L. fortunei* mussels are capable of translocation post attachment.

Temporal patterns of veliger settlement usually parallel temporal spawning patterns. The time period between spawning and settlement of *D. polymorpha* and *L. fortunei* veligers is typically 15 to 20 days (Jenner et al. 1998; Marońas et al. 2003). *D. polymorpha* and *D. bugensis* settlement occurs when shell length is about 220 μm, but settlement can happen at shell lengths between 110 to 255 μm (Sprung 1989; Sprung 1993). *D. polymorpha* juveniles are generally found in the Midwest of North America between August and September (Thorp et al. 1994). *L. fortunei* settlement ended in South America with water temperatures between 23° and 30^oC (Cataldo and Boltovskoy 2000).

Water flow patterns near the settlement surface (within 1 mm of the surface) have a significant effect upon mussel settlement, adhesion, and colonization (Venketesan and Murthy 2009). Once macrofouling organisms attach to surfaces, however, much higher flows are required to detach them (Jenner et al. 1998). Initial settlement baffles the near-surface water flow, which faciliates more settlement (Venkatesan and Murthy 2009). Adult feeding efficiency

declines with increasing flow and at about 2 m/s adults are removed from the substrate (Jenner et al. 1998). Extremely low flows did not provide enough food and dissolved oxygen, and allowed the buildup of toxic metabolic wastes (Jenner et al. 1998; Neitzel et al. 1984). Both *D. polymorpha* and *D. bugensis* are highly intolerant of oxygen deprivation, and *D. polymorpha* was more intolerant compared to *D. bugensis* (McMahon 1996). The lower dissolved oxygen threshold for *D. polymorpha* at 20$^{\text{o}}$C was 1.8 to 2.4 mg/ L (Karatayev et al. 2007). *L. fortunei* was more tolerant of low oxygen compared to *D. polymorpha* and *D. bugensis,* and had a lower oxygen threshold of 0.5 mg/ L at 20$^{\text{o}}$C (Boltovskoy et al. 2006).

       D. polymorpha, *D. bugensis*, *L. fortunei* and *M. leucophaeata* tolerated wide fluctuations in flow patterns. *D. polymorpha* and *D. bugensis* veligers settled in continuous flows less than 1.3 to 1.8 m/ s (Claudi and Mackie 1994). *D. polymorpha* generally tolerated water velocities ranging between 0.05 cm/ s to 1.8 m/ s (Claudi and Mackie 1994; Jenner et al. 1998). Isolated *D. polymorpha* adults, however, are found at 2 m/ s (Jenner et al. 1998). In European facilities, *D. polymorpha* are most abundant at flows ranging between 0.1 to 0.5 m/ s (Jenner et al. 1998). Clusters of *D. polymorpha* are detached at flows of 1.5 m/ s (Jenner et al. 1998). *L. fortunei* fouling patterns in Japanese water treatment facilities regarding water flow are comparable to *D. polymorpha*. *L fortunei* fouling generally occurred in areas of flow less than 1.2 m/ s (Matsui et al. 2002).The density of *L. fortunei* was lower in areas of flow less than 1.0 m/ s as well as areas exceeding 1.3 m/ s (Matsui et al. 2002). Some *L. fortunei* mussels are attached in velocities of 2.5 m/ s (Matsui et al. 2002). Flow velocities ranging from 0.1 m/ s to 1.2 m/ s allowed *Mytilis* spp. (blue mussels) to settle. Water velocities in the range of 1.8 to 2.2 m/ s allowed the settlement of mussels, barnacles, and hydroids in circular piping (Jenner et al. 1998), whereas flows ranging between 3.5 to 4.0 m/ s are found to prevent the settlement of marine macrofoulers (Venkatesan and Murthy 2009).

Appendix II. Foul Release Coating Mechanisms – Silicone vs. Flouropolymers

The efficacy of silicone foul-release coatings is influenced by various properties of the coating. The effects of surface free energy, coating modulus, and coating thickness on silicone performance are somewhat different compared to fluoropolymers. The incorporation of free silicone fluids (e.g. unpolymerized carbinol (hydroxyl) terminated polydimethylsiloxane oil) within silicone-based foul-release coatings significantly reduces barnacle adhesion (Kavanagh et al. 2003). Silicone coating performance is correlated with the square root of the surface free energy multiplied by the elastic modulus, which means the best silicone coatings are not simply those that have the lowest free energy (Brady 2005). The frictional slippage of silicone coatings is also important to performance (Wendt et al. 2006). The best silicone coatings have a linear and highly flexible polymer backbone that has enough substituted groups to lower surface energy but maintains backbone mobility, and adhesion to substrates (Brady 2005). Silicones are soft and rubbery, and this beneficial low elastus modulus had to be balanced against polymer strength and integrity to handle abrasion (Brady 2005). Ideal silicone coatings are smooth, stable in aqueous environments with flow velocities above 3 m/s, and resisted hydrolysis (Brady 2005). Hydrolysis of silicone coatings reduced coating mass and increased surface roughness (Brady 2005). Silicone coatings needed to be thick enough to favor interfacial fracture by peel rather than shear (Brady 2005). Fracture by peel required less force compared to shear fracture (Brady 2005). Wendt et al. (2006) showed that the critical removal force decreased with increasing silicone coating thickness. The durability of two silicone topcoats, Sylgard 184 and RTV11, also increased with increasing polymer thickness (Singer et al. 2000).

The mechanisms underlying the silicone coating performance due to these properties are not completely understood. The magnitude of force required to remove a fouling organism varied between species, silicone coatings, and oils (Holm et al. 2006). The removal stress did not vary across different coatings in the same way for all species, however, which suggested a independent variable affecting adhesion and adhesion failure between either or both the coating and the species (Holm et al. 2006). The variation in foul-release performance was dependent upon the type of free silicone fluid additive, type of coating matrix, as well as where within the coating matrix the fluid was added (Kavanagh et al. 2003). Not all silicone coatings containing free oils are effective while some silicone coatings without free oils are effective (Wendt et al.

2006). Finally, *in situ* testing of these properties on silicone performance was generally limited to free oils (Wendt et al. 2006).

Homogeneous fluoropolymers inhibit the initial bonding of adhesives. The best fluoropolymer performance occurs at surface energies closest to 20 mN/ m, meaning the surface must be extremely smooth. Fluoropolymers that had only fluorinated surface groups, and ideally CF_3 groups, exhibited the lowest surface energy (Brady 2005). The best fluoropolymers had dipoles located far beneath the coating surface; diploes are potential points of attachment (Brady 2005). Additionally, the best fluoropolymers had lots of well-organized fluorine in the coating matrix that was cross-linked with other fluorine throughout the matrix, especially the fluorine in the surface of the coating (Brady 2005). The high content, highly cross-linked fluorine helped the surface groups in flouropolymers maintain their arrangements and hence, resist the infiltration of bioadhesives and maintain stability in an aqueous environment (Brady 2005). More energy was required to remove macrofouling from fluoropolymer coatings compared to silicones, but this also meant that fluoropolymer coatings are harder and more resistant to abrasion.

Appendix III. Facility Experience with Antifouling Coatings

US Army Corps of Engineers

Coatings are not used at USACE facilities to mitigate macrofouling (A. Beitelman, pers. com.; M. Greges, pers. com.; E. Lange, pers. com.; W. Schloop, pers. com.; L. Whelan, pers. com.; L. Weigum, pers. com.; S. Winslow, pers. com.). Large-scale application of coatings at USACE facilities is not required, primarily because the severity of macrofouling does not interfere with facility operations and safety (A. Beitelman, pers. com.). Macrofouling can, however, be problematic within the cooling water system (E. Lange, pers. com.; L. Weigum, pers. com.). For example, *D. polymorpha* shells clogged the cooler condenser tubes at the RS Kerr Lock, and completely clogged a 10-cm intake pipe for a heavily colonized strainer at Webber Falls Locks (E. Lange, pers. com.).

The USACE was involved with numerous concrete and steel panel experiments and trial applications on trash racks and intake bays in the 1990s (A. Beitelman, pers. com.; W. Schloop, pers. com.). Fifteen-month experiments at Black Rock Lock conducted found that copper-, naval brass-, and bronze-thermal spray metals, copper and brass metal, a water-borne copolymer with inorganic zinc, and acrylic and other polymers with biocides were successful against *D. polymorpha* macrofouling in low flow areas (Race and Kelly 1994). Zinc thermal-spray coatings showed moderate antifouling performance. Water-borne acrylics, coatings with capsaicin powder, tin thermal-spray, aluminum-bronze sheeting, ultra high molecular weight polyethylene impregnated with a biocide, and polypropylene were unsuccessful against *D. polymorpha*. Zinc thermal-spray and galvanizing was identified as the preferred option in research conducted under the Zebra Mussel Research Program because it provided protection for corrosion and macrofouling with a lifespan of 7 to 10 years, was low cost, simple, and because zinc coatings marketed for corrosion protection did not require registration under the FIFRA. Foul-release coatings had poor durability, and antifouling coatings had a short lifespan and released biocides (A, Beitelman, pers. com.; Kelly 1998; Miller and Freitag 1992; Race 1992; Race 1992b; Race and Miller 1992; Race and Kelly 1994; Race and Miller 1994). The USACE has never investigated the legal issues associated with using biocide-based antifouling coatings in freshwater because they are never applied in large scale (A. Beitelman, pers. com.).

According to CMP, USACE applied Bioclean coatings to a total surface area of 2,787 m^2 on the steel Tug Cheraw, Tug Chetek, Tug Koziol, and Barge McCauley between 1997 and 2002

(T. Birdwell, unpublished data). USACE also applied Bioclean coatings to stainless steel trash racks (139 m^2 coated surface area) at a facility in Alton, IL in 1992 (T. Birdwell, unpublished data). No performance reports are available for these applications.

US Bureau of Reclamation

USBOR facilities on the lower Colorado River had problems with macrofouling on external structures such as trash racks and screens following infestation by *D. bugensis* in 2007 (L. Willett, pers. com.). An intake tower at Hoover Dam was dewatered and inspected in late 2007, and nearly the entire concrete surface was colonized by *D. bugensis*. Untreated steel trash racks at Parker Dam are almost completely occluded by *D. bugensis* after seven months immersion (Skaja 2009).

USBOR has not employed coatings to mitigate macrofouling at its facilities but is currently conducting panel and grate experiments on the lower Colorado River to assess its feasibility. The coating research is led by Dr. Allen Skaja, and is focused on nontoxic coatings because of the concern over drinking water and endangered species. The foul-release coatings that have been evaluated by USBOR, which are effective for a period of 15 months, are Intersleek 900 (International) and Smart Surfaces (FujiFilm Hunt Smart Surfaces). LuminOre (LuminOre), copper, brass, and bronze metal and thermal sprays were also found to be effective over the 15 month period. The foul-release coatings, however, are soft and not durable (Skaja 2009). USBOR has added several protective coatings and fluoropolymer-based foul-release coatings to the ongoing experiment.

Metropolitan Water District of Southern California

The MWD has not employed coatings to mitigate macrofouling but is also involved with panel and grate experiments. MWD uses chlorine injection to mitigate macrofouling (R. De Leon, pers. com.). MWD first started panel experiments in the 1990's in collaboration with Michigan water districts. The status of these panels is unknown. In 2008, MWD began panel and grate experiments in the lower Colorado River in high- and low-flow areas. Three coatings from the panel and grate experiments in the lower Colorado River appear promising: Intersleek 900 (International), Smart Surfaces (FujiFilm Hunt Smart Surfaces) and LuminOre (LuminOre). Polyamide epoxies, polyamide zinc rich coatings, polyurethane coatings, zinc and zinc-aluminum thermal sprays, coal tar epoxies, and hot-dip zinc galvanizing all failed in MWD tests (P. Drooks, pers. com.).

Ontario Hydro

Ontario Hydro conducted a number of short- and long-term panel experiments and trial applications. The current status of these panel experiments and the use of coatings are unknown (S. Poulton, pers. com.). Ontario Hydro released reports on their long-term coating experiments in the Great Lakes region to USBOR under a confidentiality agreement. These data were not made available for this review. A majority of the foul-release coatings tested by Ontario Hydro worked for 8 to 10 years (A. Skaja, pers. com.). Ontario Hydro also investigated biodegradable wax, copper-filled polyester, polyurethanes, ceramic-filled epoxy/ polyamine, polytetra-fluoroethylene (PTFE), seven silicones, and statically charged zinc coatings in concrete and carbon steel panel and trash rack experiments at Nanticoke Thermal Generating Station on Lake Erie (Leitch et al. 1992) that demonstrated that silicone-based foul-release coatings offered the most promise, especially Smart Surfaces (FujiFilm Hunt Smart Surfaces) (Leitch et al. 1992; S. Poulton, pers. com.). They noted that successful silicone coatings were physically weaker than the failed coatings, including the unsuccessful silicones. Statically charged zinc also provided excellent resistance to macrofouling. It appeared the DC voltage kept zinc ions at the surface without allowing rapid depletion of zinc. The other coatings that were tested were deemed unacceptable because they offered limited resistance to macrofouling compared to stainless steel controls (Leitch et al. 1992).

Ontario Hydro applied Bioclean coatings to a total surface area of 3,038 m^2 on steel trash racks at Nanticoke Steam Generating Station on Lake Erie between 1990 and 2007 (T. Birdwell, unpublished data). Ninety-five percent of the applications of Bioclean coatings to trash racks at the Ontario Hydro facility (total surface area=2,899 m^2) were done between 2006 and 2007 (T. Birdwell, unpublished data).

Ontario Hydro, Consumers Power, and Dominion Energy (formerly New England Power Company) were involved with some trial applications of the NRL duplex foul-release system, using two different silicone topcoats, RTV11 and EXSIL 2200 (GE Silicones), in the 1990s (Jones-Meehan et al. 1999), however, the NRL duplex system that was evaluated in these facilities is no longer commercially available (Wacker Silicones, pers. com.). Trash racks, intake tunnels, intake bays, and screen wells (aluminum, steel and concrete) were coated for the trial demonstrations of the NRL duplex system. The flow velocity in the intake tunnels varied in one plant between 0.4 and 2.1 m/s. The trash racks were exposed to a maximum volumetric flow rate

of 12.5 m^3/s. Coatings on trash racks were in good condition after three years (Jones-Meehan et al. 1999). The RTV11 applied to the carbon steel trash racks exhibited no *D. polymorpha* or *D. bugensis* mussel attachment after two years in cold freshwater. Inspections conducted by Ontario Hydro showed that RTV11 coatings on the intake bays and tunnels were in very good condition with minimal fouling after three and a half years of service (Jones-Meehan et al. 1999).

Consumers Energy

Consumers Energy staff was not aware of any coatings used to mitigate freshwater macrofouling in their hydroelectric facilities (L. Hannah, pers. com.). After five years of service at the Consumer Power plant, the NRL duplex coatings on both concrete and steel were in good condition, although the coated concrete exhibited #6 blisters between the topcoat and primer at a medium-dense density. Coated steel baffles exhibited 10% delamination between the topcoat and primer. Consumer Power personnel were satisfied with the duplex coating system performance on the concrete tunnel walls and steel deflecting vanes of the intake bay. RTV11 was 99% effective against *D. polymorpha* and *D. bugensis* mussels at Consumer Power after a three-year period. After five years of service, the duplex coating system had low concentrations of *D. polymorpha* that could be easily wiped away (Jones-Meehan et al. 1999).

Dominion Energy (formerly New England Power Company)

Dominion Energy encountered durability issues with RTV11 topcoat used in the NRL duplex system. RTV11 applied in the intake tunnels was damaged by *Crepidula* snails. This facility used brackish water for cooling purposes. The *Crepidula* snails dug into the silicone topcoat and exposed the Silgan J-501 tie coat. Additionally, there was approximately 20% delamination at the epoxy-tie coat interface on the screen walls after more than one year in service. The delamination was attributed to improper application (i.e. damp conditions and inadequate topcoat thickness). No delamination occurred in intake tunnels (Jones-Meehan et al. 1999).

Dominion Energy applied Bioclean coatings to a total surface area of 18,906 m^2 on intake tunnels, intake bays and screen wells between 1995 and 2008 at its Brayton Point Units 1,2 and 3, Narragansett Electric Units 9,10 and 11, and Salem Harbor Units 1,2 and 3 facilities. The Bioclean were made to concrete and cast iron components. Fifty-five percent of the surface area (10,479 m^2) of Bioclean application was done on intake tunnels/ screen wells, 33% (6,104 m^2) on

intake tunnels, and 12% (2,323 m^2) on intake bays/ intake tunnels (T. Birdwell, unpublished data).

According to Fuji Hunt Smart Surfaces (FHSM), Dominion Energy applied Smart Surfaces coatings to concrete intake tunnels #11 and #12 on Unit 1 of the Brayton Point facility in 1996. Visual photographs and notes provided by FHSM indicated that, after approximately 1.5 years, the #11 intake tunnel and tunnel control gate were free of mussels and tunnel #12 showed minor growth. FHSM claimed this application of Smart Surfaces was trouble free for approximately 12 years from 1996 to March 2008.

Long Island Lighting Company

The Long Island Lighting Company (LILCO) conducted short- and long-term panel experiments and trial applications with numerous coatings in coastal facilities. LILCO began experimenting with coatings in 1981 with small and large scale applications of ablative copolymers containing cuprous oxide or organotin in intake bays. Panel experiments with nontoxic coatings were initiated in 1987 and evaluations were expanded large-scale trial applications of successful products on intake bays, intake tunnels, cell blocks, and trash racks. Bioclean (CMP), Biox (Kansai), Epco-Tek (Hi-Tek), EXSIL 2200 (General Electric), and Wearlon (Decora) were evaluated in the large-scale trial applications. LILCO was pleased with the performance of Bioclean, Biox and Epco-Tek. Use of Bioclean on intake tunnels, essentially eliminated annual cleaning requirements, and there are few problems with adhesion and delamination. Biox was colonized each year and required annual cleaning but the macrofouling would slough off with dewatering. Biox showed no signs of delamination or problems with adhesion. Epco-Tek exhibited very little colonization for two years and was moderately fouled after three years. Epco-Tek was resistant to abrasion and did not delaminate. LILCO reported excellent to good antifouling performance on Epco-Tek panels immersed in marine waters for two years and one panel was reported to show excellent antifouling performance for four years. EXSIL 2200 applied to a concrete intake bay in a coastal plant exhibited only a few barnacles and hydrozoans after two years, but was heavily fouled with one-half inch mussels by the third year. They found that EXSIL 2200 applied to a concrete intake bay showed approximately 30% delamination between the Plastocor primer and the silicone topcoat after two and a half years (Gross 1997).

LILCO applied Bioclean coatings to a total surface area of 16,052 m^2 on intake bays, intake tunnels, cell blocks, and intake wells between 1988 and 1998 at Port Jefferson Units 1 and 3, Glenwood Units 4 and 5, Northport Units 1,2,3, and 4, and E.F. Barret Unit 2 plants. Bioclean was applied to both concrete and steel at these facilities (T. Birdwell, unpublished data). Intake bays were the most commonly coated facility component (69% surface area, 4,937 m^2 on 25 bays) followed by intake tunnels (29% surface area, 2,117 m^2 on 13 tunnels) (T. Birdwell, unpublished data).

Pacific Gas and Electric

Pacific Gas and Electric (PGE) conducted laboratory tests and applied two silicone foul-release coatings, Bioclean and Biox, to mortar-lined 2.1-m diameter conduits, concrete intake tunnels, the interior frameworks of traveling screens and intake structures at Diablo Canyon Power Plant in the late 1990s and at Moss Landing Power Plant in 2001 (T. Birdwell, unpublished data). The silicone topcoat at Moss Landing was abraded due to suspended sediment, especially the unit closest to the ocean (D. Innis, pers. com.). Laboratory tests showed favorable performance of silicone coatings over a two-year period (EPRI 1992).

Potomac Electric Power Company

Potomac Electric Power Company (PEPC) evaluated Intersleek foul-release coatings during trial applications to trash racks at Chalk Point Station. Intersleek reduced macrofouling. The time required for cleaning the coated trash racks, however, was comparable to the untreated trash racks because the Intersleek coated trash racks were less durable and different cleaning practices were required (EPRI 1992).

Tampa Electric

Tampa Electric (TECO) conducted trial applications to evaluate the effectiveness of several silicone coatings against macrofouling. TECO applied an organic polysiloxane resin to a concrete intake tunnel and steel elbow on unit 3 at the Gannon Station. Inspections after seven months showed that surfaces were nearly free of micro- and macrofouling. A few barnacles and grass had attached but were easily removed. Fouling patterns on the steel elbow reflected flow patterns. The outside bend of the coated steel elbow was 40% covered with algal slime and barnacles at a density of 11-22 barnacles/m^2, but the inside bend of the elbow was free of all fouling. TECO applied a silicone elastomer coating to fine-mesh, traveling screen polyurethane

baskets and to steel frames at its Big Bend Station. The silicone elastomer coating was 50-90% fouled with barnacles after seven months of service, and significant force was required to remove fouling. It was noted, however, that only one topcoat was applied instead of the recommended two coats (EPRI 1989).

TECO applied Bioclean coatings to a total surface area of 13,775 m^2 on intake tunnels and intake bays between 1988 and 2007 at Gannon Units 1 and 3, Big Bend Units 1,2,3, and 4, Bayside Unit 2, and Bayshore Unit 1 plants. Intake tunnels were the most commonly coated TECO facility component (81% surface area, 11,168 m^2). Bioclean was applied to concrete, steel, stainless steel, fiberglass, and copper coated concrete at TECO facilities (T. Birdwell, unpublished data).

Consolidated Edison Company (includes former Commonwealth Edison)

Consolidated Edison Company (Con Ed) performed several *in-situ* evaluations of foul-release coatings at their Astoria and Monroe facilities. A silicone elastomer was applied to the walls of an intake bay, and an organic polysiloxane resin was applied to several trash racks at the Astoria Station. After an unspecified period of time, the silicone elastomer applied to the intake bay was fouled, but fouling was easily removed. The coating reduced mussel accumulation in the heat exchanger. Localized delamination of the silicone elastomer applied to the intake bay was reported, which was attributed to the conditions during application. No performance evaluation is available for the organic polysiloxane resin coating on the trash racks (EPRI 1989). Kovalak et al. (1993) noted that coatings were evaluated at Monroe, and reported the most promising were silicone-based. He also noted that silicone-based coatings may not be cost-effective because of lifespan. Concerns of lifespan involved the integrity of the material, which was applied during outages scheduled in late fall or late winter to early spring when it was be difficult to dry dewatered components. Bioclean coatings were applied to steel submersible fire pumps (32.5 m^2) at the Waukegan Station (T. Birdwell, unpublished data).

Florida Power Corporation

Florida Power Corporation (FPC) coated a 15-cm diameter pipe at the Crystal River Station with a silicone elastomer, a modified silicone resin, and an organic polysiloxane resin. Inspections after one year revealed that some microfouling growth had occurred on all coatings, but the fouling dried and peeled away from coating surface during the period required for inspection. Inspections after three years, showed that the modified silicone resin performed well

and the other two coatings had developed algal fouling that was easily removed (EPRI 1989). FPC applied Bioclean coatings to 7,067 m^2 of a concrete intake tunnel at its P.L. Bartow facility in 1989 (T. Birdwell, unpublished data).

San Diego Gas and Electric

San Diego Gas and Electric (SDG&E) coated several intake bays of its South Bay Station with a silicone elastomer coating. Micro- and macrofouling was reported in two intake bays after 16 months service to the extent that 65% and 85% of the surfaces were fouled. Fouling, however, was easily removed. In one of the bays, a small area of delamination was observed where the coating tie coat separated from the layer underneath. Observations on the other intake bay after 29 months showed that the silicone elastomer coating was in good condition. SDG&E reported that the coating produced less outage time because cleaning was reduced for condenser water boxes (EPRI 1989).

Electric Power Research Institute

The Electric Power Research Institute (EPRI) undertook an evaluation of many coatings in the late 1980s and 1990s and collaborated with many power companies in these efforts. The EPRI evaluated 23 coatings on concrete and steel panels at Battelle Marine Laboratory at Daytona Beach, FL in an immersion experiment and conducted accelerated corrosion tests to estimate coating lifespans. The 23 coatings that were evaluated included modified silicone resin, acrylic silicone, organic polysiloxane resin, silicone acrylic copolymer, silicone elastomer, fluorourethane, phenolic resin bonded PTFE, epoxy bonded fluoropolymer, thermoplastic resin bonded PTFE, resin bonded fluorocarbon blend, fluorocarbon polymer, PTFE coating, 100% solids multifunctional epoxy, 100% solids 2-component epoxy, natural polymer, 100% solids elastomeric urethane, hydrophilic copolymer, PTFE coating with antibiotic additive, copper-nickel alloy, thermal-sprayed copper-nickel, and copper copolymer coatings. Additionally, EPRI conducted *in-situ* concrete and steel panel experiments at Pilgram Nuclear Generating Station (Boston Edison), Astoria Power Station (Astoria Energy LLC), Chalk Point Power Station (PEPC), Cape Canaveral Power Station and Fort Myers Station (Florida Power and Light Co.), Nueces Bay (Topaz Power Group), and South Bay Power Station (SDG&E) (EPRI 1989).

The coating names and manufacturers were not provided by EPRI to maintain confidentiality, but several important conclusions were drawn from their evaluations. Fouling-

release coatings fouled, but were easily cleaned, and silicone foul-release coatings performed satisfactorily after two years immersion in seawater. The silicone elastomers and organic polysiloxane resins performed the best out of the evaluated coatings, and had a predicted lifespan between two and four years. The performance of foul-release coatings was related to water velocity. The application costs for foul-release coatings ranged between $54/m^2 and $108/m^2, but the coatings were cost effective when compared to costs of manual cleaning. Finally, they reported that copper-based coatings could be utilized by utilities under the USEPA effluent limitations on copper release at the time of publication (EPRI 1989).

Chugoku Marine Paints

Chugoku Marine Paints (CMP) provided a Bioclean application history for all North American facilities that installed Bioclean SPGH or earlier versions of Bioclean. The data provided included the date of application, utility, plant-unit, facility component, substrate material, surface area of application, and renewal remarks. According to CMP, between 1988 and 2008, Bioclean coatings were applied to marine and freshwater hydropower facilities for 18 North American water and power companies. Utilities that applied Bioclean coatings to components at their plants and facilities included LILCO, TECO, PGE, FPC, Ontario Hydro, Boston Edison, Virginia Power, Carolina Power and Light, USACE, Tennessee Valley Authority, Commonwealth Edison, Wisconsin Public Service, Houston Light and Power, Dominion Energy (formerly New England Power), Florida Power and Light, Keyspan, Southern California Edison Company, and Constellation Energy. Six North American utilities in the period between 1988 and 2008 reapplied Bioclean coatings. TECO and Carolina Power and Light have reapplied Bioclean coatings three times since 1988 (T. Birdwell, unpublished data).

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