Ref. No. [UMCES]CBL 2014-017

The Biology of *Garveia franciscana* and Potential Options to Limit Impacts of Cooling System Fouling

Maritime Environmental Resource Center

August 2014

Prepared for: Calvert Cliff Nuclear Power Plant

Questions and comments should be directed to:
Dr. Mario Tamburri
Maritime Environmental Resource Center
Chesapeake Biological Laboratory
University of Maryland Center for Environmental Science
PO Box 38 / 146 Williams Street
Solomons, Maryland 20688, USA
Email: tamburri@umces.edu

Table of Contents

Page No.

1. Background and Objectives

On October 11, 2013, staff from Constellation Energy Group and the University of Maryland Center for Environmental Science (UMCES) Chesapeake Biological Laboratory (CBL) met to discuss an ongoing problem that Calvert Cliffs Nuclear Power Plant (CCNPP) is experiencing resulting from colonization and growth on intake pipes by the rope grass hydroid (*Garveia franciscana*) (Torrey 1902). Large colonies of this hydroid form on intake pipes of the CCNPP cooling water system, potentially reducing flow of cooling waters and periodically but unpredictably breaking loose, clogging filter screens and impacting pump performance. This hydroid from the family Bougainvillidae is a common fouling organism and a widely distributed non-native or invasive species in the Chesapeake Bay.

Based on discussions between Constellation and CBL staff, it was agreed that the first step in addressing this issue would be a review of existing information and options. This report completes Task 1.1 – A review of the biology, life history and physiological tolerances of *G. franciscana*, and Task 1.2 – A review of three potential categories of approaches for controlling or minimizing impacts *G. franciscana* cooling pipe fouling: (a) water treatment, (b) pipe coatings, and (c) mechanical control. Based on this information, recommendations on additional experiments, testing and trial applications will be made.

2. *Garveia franciscana* Biology

2.1. Background

Garveia franciscana (commonly known as the rope grass hydroid) is a colonial marine hydroid (Cnidaria, Hydrozoa, Anthomedusae, Bougainvilliidae), and a very common sessile organism in temperate and subtropical estuaries (Thompson 1993). Hydroids are a class of marine invertebrate, closely related to sea anemones and corals, which are often mistaken as seaweeds when attached and growing to hard substrates such as rocks and pilings (Figure 1). Some have branching stems and others just have simple stalks.

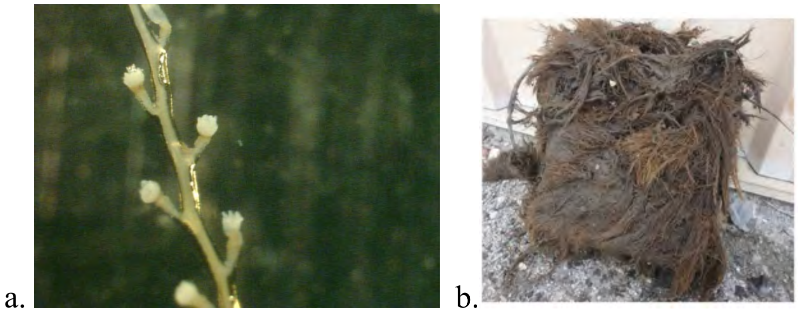

Figure 1. Photos of *Garveia franciscana* : a. (Fofonoff et al. 2003) and b. (Zammit et al. 2013).

The native range of *G. franciscana* is unknown; however, it is suggested that the species has native populations in both India/Indian Ocean and East Brisbane/Queensland/Brisbane River, Australasia (Fofonoff et al. 2003). This hydroid exhibits broad tolerances to environmental conditions (Table 1) and has proliferated as an invasive species in many areas. It is known to be present in Europe, the Black and Azov Seas, West Africa, India, Australia, California (San Francisco Bay in 1901), the Atlantic coast of North America, the Gulf of Mexico, Panama, and South America. *G. franciscana* is most successful under estuarine conditions, and is capable of surviving in both tropical and temperate climates (Vervoort 1964; Figure 2).

Table 1. Environmental Tolerances of *Garveia franciscana.* See Davidson et al. (2007) and Fofonoff et al. (2003) for more details and additional experimental references. See Thompson (1993) for estuarine field and laboratory studies (James River, VA).

Parameter	**Maximum**	**Minimum**	**Optimal**
Water Temperature (°C)	30 - 35	0 - 12	10 to 32
Salinity (ppt)	23 – 35*	0 – 1*	5 to 25
Reproductive Temperature (°C)	34*	9*	15 to 32*
Reproductive Salinity (ppt)	25	5	10 to 15

* Experimental

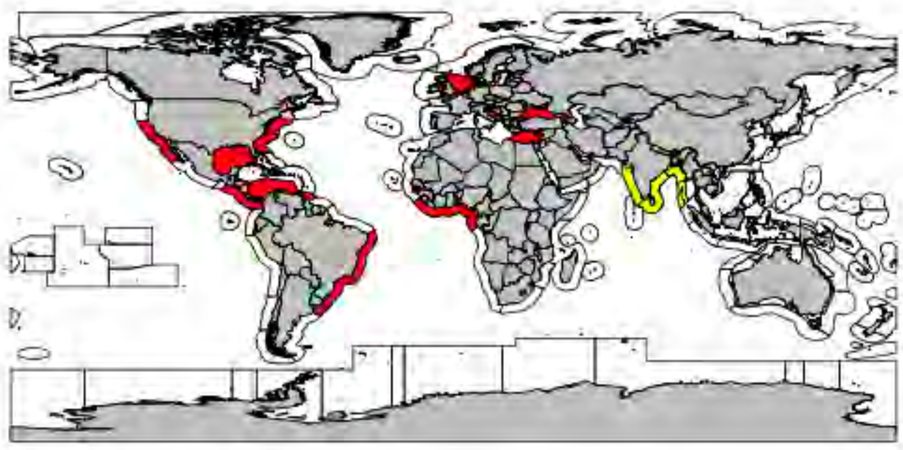

Figure 2. Range of *Garveia franciscana* taken from NEMESIS Bioregion Distribution (Fofonoff et al. 2003).

2.2. Life History

Hydroids use stinging cells to stun their prey (zooplankton and epibenthic animals), and tentacles transport the food in the mouth and down to the interconnected branches where it is digested and distributed to the colony (Lippson and Lippson 2006).

Most hydroids reproduce through gonophores (reproductive polyps) that produce microscopic free-floating hydromedusae. The hydromedusae produce planula larvae (flattened, ciliated, bilaterally symmetrical larvae) that eventually settle onto hard substrate to form the hydroid colony. *G. franciscana* lacks a hydromedusae stage and reproduces sexually using gonophores. Male and female gonophores are born on separate colonies (Vervoort 1964). Eggs are fecundated in situ (one egg in each female gonophore) and develop into a complete planula inside the gonophore. The fully developed planula leaves the gonophore after rupture of the peridermal covering. Planula larvae then settle onto hard substrate and eventually produce a mature hydroid colony.

Planula settle and attach to a variety of solid substrates (stones, wood, rope, concrete). After attachment, growth is vertical to help facilitate feeding, and then becomes horizontal as the colonies spread (Vervoort 1964, Stone and Webster Engineering Corp. 1992). Colonies become reproductive 19-27 days after planula settlement (Turpayeva et al. 1976, Stone and Webster Engineering Corp. 1992). Evidence suggests that *G. franciscana's* growth rates are dependent on food supply and environmental conditions such as water temperature and salinity (Vervoort 1964, Calder 1990). In temperate latitudes, reproduction has been observed from June to September as long as temperatures remained above 14 °C (Schuchert 2007). Individual colonies grow from about 1-10 cm and often twist themselves into ropes over 30 cm high (Schuchert 2007, Lippson and Lippson 2006).

In the Chesapeake Bay, near CCNPP, epifaunal growth plate studies (Cory 1967, Abbe 1987) describe a "yearly climax" community with growth beginning in spring, maximum biomass in summer, a late-summer die-off and little to no growth during the winter months. Hydroids were shown settling from April to June with *G. franciscana* actively colonizing in July and extremely abundant in September (Abbe 1987). There were a few colony clumps still observed over the winter months. During the summer growth period, colonies measured 50-65 mm in length on monthly panels and up to 80 mm on 3-month panels (Cory 1967).

2.3. Tolerances

2.3.1. Environmental Conditions

Both laboratory and field experiments and observations have shown *G. franciscana* to tolerate exposure to freshwater and survive in salinities up to 35 ppt (Crowell and Darnell 1995, Thompson 1993). *G. franciscana* is highly abundant in oligohaline to low-mesohaline waters and thrives best at salinities between 5 - 15 ppt (see Table 1).

Laboratory and field studies were performed at the Surry Nuclear Power Station (see Section 8 for additional information) to test the effects of low dissolved oxygen (DO) and varying salinities on *G. franciscana* (Stone and Webster Engineering Corp. 1992). Both sets of experiments showed that low DO resulted in loss of polyps during at all treatment durations (1, 3, 5 or 7 days), but at all concentrations (6.8, 0.5 and 0.1 mgL^{-1} O_2), *G. franciscana* was able to recover eventually. Recovery was faster in salinity of 10 ppt than in 20 ppt. Only under anoxic (0 $mg\ L^{-1}$ O_2) conditions were colonies killed with no re-growth.

Thompson (1993) found that *G. franciscana* declined in salinities over 30 ppt, maintained itself in a salinity of 15 ppt and grew well in 5 ppt. Studies on a similar species (*Bimeria franciscana*) showed that hydroids could tolerate short periods of exposure to freshwater and survive in salinities up to 35 ppt (Crowell and Darnell 1955). It is hypothesized that *G. franciscana* may exhibit a behavioral adaptation to osmotic stress by maintaining polyps as buds during exposure to stressful salinities and reducing the surface area exposed to the environment (Thompson 1993).

Laboratory and field experiments were conducted on *Ectopleura larynx* (marine hydroid) collected from cage nets of Atlantic salmon farms in Norway near the Institute of Marine Research facility (Guenther et al. 2011). Results of this study showed that short-term immersions in heated seawater at temperatures of 50 and 60°C significantly reduced the settlement and survival of *E. larynx*. Actinulae (a type of hydroid larvae) settled well after 1 or 3 seconds of immersion in water at temperatures of 30 and 40°C. After immersions at 50°C, no actinulae settled. None of the juvenile hydroids survived after being immersed at 50 or 60°C and exposure of adult hydroids to 50°C for 1 and 3 seconds resulted in very low survival. Exposure to 60°C seawater killed all of the adult hydroids.

2.3.2. Biocides

Laboratory experiments showed short-term immersion in acetic acid had detrimental effects on the settlement of actinulae and survival of both juvenile and adult hydroids (Guenther et al. 2011). Decreasing survival of hydroids at increasing concentrations or immersion times was observed. None of the juvenile or adult hydroids survived the 5-minute exposure (0.2 and 2 % concentration). All exposure times to 2% concentration of acetic acid reduced the settlement of larvae and survival of hydroids to less than 10%.

Field experiments have also shown significant effects of both heat (50 °C for 1 and 3 second) and acetic acid (0.2% for 1 and 5 minutes and 2% for 1 and 3 seconds) (Guenther et al. 2011). The biomass (wet weights) of organisms decreased 2-5 days after treatment. There appeared to be more effect on biomass from acetic acid exposure. The authors suggest that a combination of heat and acetic acid (possibly using a 5% concentration of acetic acid) would be most effective in treating finfish farm netting for biofouling due to *Ectopleura larynx*.

G. franciscana has been found to tolerate 200 $\mu L\ g^{-1}$ of copper (Crooks et al. 2011). Field experiments (de Rincon and Morris 2003) measuring the settlement of *G. franciscana* on different materials (steel, aluminum, copper, Plexiglas, glass, carbon steel, polyethylene and zinc alloy) found that the hydroid had greater adherence on the non-metal surfaces and did not grow on materials with more than 30% copper.

Theede et al. (1979) conducted laboratory cadmium tolerance tests on *Laomedea loveni* and found that the acute toxicity of cadmium on the hydroid was strongly modified by abiotic factors. *L. loveni* was more tolerant to cadmium at lower temperatures and high salinities. The resistance to cadmium decreases with rising temperatures. The lowest cadmium concentration affecting retraction of the polyps is 3 $\mu g\ L^{-1}$ at 17.5 °C and 10 ppt.

At the Surry Nuclear Power Plant in Virginia, several biocides in addition to chlorine (sodium hypochlorite and sodium bromide are now used as fouling control) were tested against *G. franciscana*, including ammonium hydroxide, hydrogen peroxide, sodium bromide-hypochlorite mixture, a surfactant mixture (ClamTrol), and chemically induced anoxia. However, at doses allowed by their U.S. EPA permit, these treatments were ineffective (Stone and Webster Engineering Corp. 1992, see Section 8).

3. Limiting Impacts on Cooling Pipe Fouling

3.1. Problem Statement

Constellation would like to identify, evaluate and implement a fouling control strategy, that specifically prevents the settlement and/or extensive growth of *G. franciscana* in the cooling system of CCNPP, and to eliminate or significantly reduce the need for unplanned cleaning of screens, water tunnels, and waterboxes.

While CCNPP experiences fouling due to a variety of organisms growing in and near the plant, by far the most problematic is *G. franciscana*, which can significantly alter plant operations. All gradual biofouling buildup in the cooling systems will ultimately result in lost generation of power and increase maintenance costs during planned cleaning. However, it has been observed that the gradual accumulation of most estuarine fouling organisms can be managed effectively with anti-fouling coatings and scheduled, periodic maintenance. In contrast, the rapid seasonal growth of *G. franciscana*, and unexpected release or sloughing of large clumps, leads to emergent cleanings that can result in significant disruption to the quarterly system schedule week and potential penalties for unplanned power reduction.

Constellation has considered several options in the past, including debris filters (rejected as a mitigating strategy) and mechanical cleaning of tunnels while in service (unacceptable due to resulting loss in power production during cleaning and elevated plant risk). A silicone fouling-release coating has been applied to the CCNPP water tunnels and appears to be fairly successful at limiting the growth of most organisms, but has had little, if any, noticeable impact on the growth of *G. franciscana*.

The challenges associated with biofouling of power plant cooling systems are ubiquitous and several facilities have also noted problems associated with *G. franciscana*. The most common approach to address cooling system biofouling for power plants has been the application of chlorine in various forms. This report reviews various options and approaches, and, based on CCNPP operational requirements and logistic limitations, will provides recommendations for additional pilot-scale assessments and future full-scale applications.

4. Water Treatment

The industrial treatment of water dates back to the 19th century, and includes well-studied disciplines such as drinking water and wastewater engineering. The treatment of water to prevent fouling has also been utilized for many years and typically involves the use of chlorine or other common oxidants (e.g., ozone). However, because of concern about and regulated prevention of the spread of aquatic organisms (bacteria, phytoplankton and zooplankton) from ships' ballast water, there have been significant investments, research and development, and advancement of several options that might also be effective in large-scale anti-fouling applications.

Like all new investments in equipment, there are several aspects to consider prior to making a final decision, including:

- Treatment flow capacity;
- Ease of use (level of expertise/training required);
- Consumables issues including costs, amounts required, risks to user, and storage;
- Initial investment/costs;
- Short and long-term maintenance time and costs;
- Cost and availability of spare parts;
- Positive or negative effects on the system being treated (e.g., corrosion);
- Power requirements; and
- Permit requirements (in some cases).

This section and the case studies in Section 8, below, review traditional fouling control water treatment options and present other options being used for ballast water treatment. The majority of information for Section 4 was gathered from reviews by Venkatesan and Murthy (2008), Satpathy et al. (2010), Lloyds Register (2010), and the EPA Science Advisory Board (2011), in addition to several website resources.

4.1. Biocides

Biocide treatments introduce either an oxidizing or non-oxidizing chemical into water to disinfect, inactivate or kill aquatic organisms. In general, oxidizing agents disrupt the organism's cell structure, while non-oxidizing agents typically disrupt cell functions such as metabolism or reproduction. The dose and time requirements to kill organisms, and the time required for chemical degradation, is determined by the specific organisms being treated and local water quality conditions (i.e., salinity, temperature, pH and organic concentrations).

4.1.1. Oxidizing Agents

An oxidizing agent (also called an oxidizer or oxidant) is a chemical compound that readily transfers oxygen atoms. Oxidizing agents disrupt an organism's cell structure. They are very effective, but human/environmental hazards and EPA discharge regulations must be considered. It is important to understand the changing oxidant demand conditions of the water being treated (e.g., particulate and dissolved organic levels) to optimize dose (i.e., avoid under- and over-dosing). In some cases, treatments employing oxidants may also need to include chemical neutralization (e.g., sulphite or bisulphate) prior to discharge to meet discharge requirements and avoid environmental impacts.

4.1.1.1. Sodium hypochlorite (inline/onsite electrolysis or liquid injection, commercially available for fouling prevention)

Chlorine is currently the most common method for controlling biofouling in water and wastewater treatment facilities, as well as in industrial uses. Sodium hypochlorite is by far the most common chlorination compound employed. Other forms include chlorine gas and chlorine dioxide, which are described below. Treatment systems typically use either liquid injection or electrochlorination (i.e., electrolysis). Like all biocides, the production of disinfectant by-

products may be a concern with chlorination (e.g., chlorinated hydrocarbons and tri-halomethanes) and they should be monitored for environmental safety.
Liquid sodium hypochlorite has proven to be effective, is easily available and the purchase cost is relatively low. However, safe transport and handling, and on-site storage of large volumes should be taken into consideration.

Electrochlorination uses a direct current to create an electrolytic reaction to transform salts in seawater into sodium hypochlorite; thus, no liquid chlorine is stored on-site. Both systems may need supplementary brine to be effective in low salinity (typically less than 10 ppt) and freshwater. The initial startup costs, power consumption, and system complexity (which may require more training) of electrochlorination systems should be weighed against the constant influx of liquid chemicals, the storage footprint, and the safe handling of a liquid chlorination system.

Both experimental studies and actual full-scale operational applications have demonstrated that chlorine residual doses as low as 1.0 ppm can prevent settlement and growth of invertebrates (Venkatesan and Murthy 2008, Surry Nuclear Power Station personal communication). However, an intermittent or pulse chlorination dose of 1.2 ppm at a frequency of 0.5 to 2 hours was sufficient to control the settlement and growth of higher organisms and slime formation. As described in the case studies below (Section 8), a pulsed approach of dosing the cooling water system with relatively low doses of sodium hypochlorite at less than 3.0 ppm for 2 hours every 24 hours can meet EPA discharge requirements and be effective at controlling *G. franciscana* and other fouling growth. However, some applications of pulse chlorination to control the growth of *G. franciscana* have not proven successful (Entergy Sabine Power Station, personal communication).

Examples:
A. Evoqua Water Technologies, Chloropac
Chloropac systems from Evoqua Water Technologies are designed to help keep intake and cooling water systems free of biofouling, and help maintain the efficiency of heat transfer. Chloropac systems are designed and manufactured in fully-assembled, multi-skid packages. The Chloropac electrolytic cell assembly consists of two concentric titanium tubes between which salt water (seawater) flows. By passing electric current through the salt water, Chloropac converts sodium chloride into sodium hypochlorite. Chloropac does not require back-flushing or periodic cleaning. The cell has been specifically designed to operate with turbulent high velocity flows over the total electrode surface, preventing precipitation of magnesium and calcium hydroxides, and keeping the cell continuously clean of calcareous deposits.

B. NALCO, Cooling Water Treatment Biocontrol
NALCO provides oxidizing biocides to control cooling water biofouling, including open recirculating cooling towers, once-through cooling systems, closed loop cooling systems, and cooling ponds. A combination biocide approach is currently used to control the growth of *G. franciscana* and other macrofouling organisms at another power plant on the Chesapeake Bay. The combination includes injection of liquid sodium hypochlorite and the NALCO patented Acti-Brom (sodium bromide, described in Section 4.1.1.2.) that may reduce the amount of oxidizing biocide required to control fouling in cooling water.

C. MIOX Corperation, Mixed Oxidant Solutions
MIOX claims to have a new onsite generation technology that produces a mixture of disinfectants by electrolysis. The MIOX fouling prevention systems creates a dilute solution of 0.40% sodium hypochlorite with traces of hydrogen peroxide and other reactive oxygen species. This approach is at the center of the new treatment regimen designed by MIOX's partner New Technology Systems to combat biofouling at power plants but it is unclear how it is different than standard electochlorination and it is possible that other similar onsite electrolysis systems produce the same suite of oxidants.

4.1.1.2. Sodium bromide (liquid injection, commercially available for fouling prevention)
Sodium bromide is another oxidizing biocide and is marketed under the name Acti-Brom 7342 (42.8 % sodium bromide and 57.2 % inert ingredients) for use in fouling control by NALCO. Sodium bromide is meant for use in combination with another primary oxidant, such as sodium hypochlorite, to reduce the amount of biocide required (i.e., a "chlorine enhancer"), and provides a source of hypobromous acid when applied to cooling water systems. Sodium bromide is also highly soluble and has a high density, which permits large amounts of liquid bromine monochloride to be supplied in small container. While there is a cost associated with the addition of more than one biocide, the use of sodium bromide might reduce overall costs when meeting discharge requirements is taken into account. Additional information on this approach is provided below in Section 8.

4.1.1.3. Ozone (inline generation, commercially available for fouling prevention)
Ozone is also a common water treatment approach. Ozone gas is produced by an ozone generator and is bubbled through the water. While it has been used safely and effectively in several applications for many years, including cooling system fouling control, ozonation of saltwater results in the production of bromate by-products, which may be harmful to the environment. Other potential limitations include challenges in achieving uniform distribution of ozone throughout a system and the relatively high cost of treatment for large-scale applications. These have largely restricted the use of ozone for treatment of potable water and sewage. However, at one location, ozone is being re-evaluated as a method for controlling *G. franciscana* fouling because a pulsed chlorination attempt was unsuccessful (Entergy Sabine Power Station, personal communications).

Examples:
A. Wedeco (Xylem), Effizon HP technology
Wedeco Effizon ozone installations have been integrated into and used for many years in cooling systems of many areas of power production. The Wedeco system is designed to be turnkey and operated in a fully automatic mode.

B. Other providers include GE Water & Power, Senozone Services Ozonation, AirTree Ozone Technology, and Primozone BioFoulControl.

4.1.1.4. Chlorine dioxide (liquid injection, commercial)
Chlorine dioxide is available for fouling control applications and is similar in many ways to the injection of liquid sodium hypochlorite. However, to produce chlorine dioxide, large volumes of concentrated sulfuric acid and hydrogen peroxide must be stored on-site and mixed in appropriate ratios prior to injection.

4.1.1.5. Peracetic acid (liquid injection, experimental)

Peracetic acid, a derivative of hydrogen peroxide, has been considered for fouling control for organisms such as zebra mussels. Peracetic acid has been explored or applied in a variety of water treatment applications or as a disinfectant and has potentially fewer hazardous by-products. However, effective dosage levels are relatively high, which require large storage volumes and results in increased costs. As with all chemical treatments, peracetic acid also requires safe handling practices.

4.1.2. Non-Oxidizing

Non-oxidizing agents disrupt cell functions such as metabolism or reproduction. Like oxidizing biocides, the time needed to impact organisms and for chemical degradation may in some cases be dependent on species being treated and affected by local water quality. A few specific biocides have been considered for industrial scale water treatment, including the injection of liquid menadione, alkylamines, gluteraldehyde, and acrolein. However, all of these non-oxidizing biocides are still in the experimental stages, and are therefore not being considered at this time.

4.2. Physical Disinfection

Physical disinfection systems use non-chemical means to inactivate, disrupt, or kill organisms.

4.2.1. Ultraviolet Radiation (commercially available for fouling prevention)

Ultraviolet (UV) light destroys cell membranes and either kills outright or alters cell structures to inhibit organismal functions such as reproduction. UV is effective against many organisms from viruses to the larvae of marine invertebrates. This method is frequently employed in municipal and industrial water treatment where the percent UV transmittance (%UVT) of the water is high at the time of treatment. In these environments, UV treatment is generally low-power, and therefore cost-effective.

UV treatments are unlikely to be effective in turbid coastal waters with a low %UVT. The %UVT can be negatively affected by various typical environmental factors in estuarine systems, such as high dissolved organic carbon concentrations, high turbidity, increased sediment load caused by storms or large plankton blooms. These conditions likely require either a higher UV dose/power per lamp or more UV tubes, resulting in higher power usage; or by reducing the water flow rate, which may not be possible.

It is also important to note that UV is only able to treat organisms that are exposed to the UV radiation, so all water entering the cooling systems must be treated continuously. Given the large flow rates and volumes of cooling water used by power plants, UV treatment is likely to be cost prohibitive and not feasible.

4.2.2. Deoxygenation (experimental)

Producing lethal levels of oxygen (hypoxia or anoxia) can be an effective approach at controlling or killing aerobic and higher organisms. Deoxgenation can be achieved through the addition of oxygen-stripping chemicals (e.g., sodium bisulfite and ammonium bisulfite), injection of inert gas (typically nitrogen and carbon dioxide), or inducing a vacuum to remove the oxygen in the water, thereby asphyxiating the organisms. The treated area must be sealed and vented with one-way flow, but water is re-aerated quickly upon discharge. Given the tolerance of *G. franciscana* to low oxygen conditions, this approach may have limited success and maintaining deoxygenated conditions can be costly.

4.2.3. Heat (experimental)

A heat system that increases water temperature to a point where organisms are killed is energy intensive. Cysts and some bacteria can require very high temperatures, but organisms like bivalves are killed after approximately one hour at 40°C. Water flow disruption is not appropriate in this application, but typically is necessary to raise temperatures adequately. Microwave heating is being tested, but is currently not cost effective.

4.2.4. Ultrasonic/Ultrasound (experimental)

Ultrasound systems disrupt an organism's cell wall by using high frequency vibrations that cause microscopic bubbles. Vibration intensity and exposure length vary. Low frequencies appear to be the most effective. Some indications are that free-field ultrasonic radiation is effective in highly turbid environments, but costs to implement industrial scale applications are not known.

5. Coatings

The types of coatings on the market are classified as either containing a biocide or biocide-free. Biocide containing coatings include antifouling paints, epoxy based, and fluorinated powder coatings. Biocide-free coatings are marketed as non-toxic because they rely on low surface energy properties to reduce biofouling.

5.1. Biocide Coatings

Antifouling coatings prevent organisms from attaching by carefully controlling the release of biocides. There are typically three components: a binder (polymeric compound to hold the paint together), a resin (water-soluble compound to allow seawater access to toxin), and a toxin/biocide (to confer antifouling property to the paint) (Nair 1999). The coatings are solid metals or in powdered form with the biocide incorporated into a coating matrix. Incorporation methods include galvanization and thermal spray. When the coating erodes and sloughs off, the embedded biocides are released (Wells and Sytsma 2009).

The efficacy of different antifouling coatings varies with target species. For example, copper is highly effective against macrofoulers, but not microfoulers (e.g., algae). For this reason, booster biocides are often used alongside metals. On January 1, 2008, the International Maritime Organization banned coatings containing tributyltin (TBT) because of toxicity concerns (Wells and Sytsma 2009).

Most antifouling paints have a lifespan of one to two years in flowing water. Performance is approximately three years in static water (Skaja 2012). Copper, copper alloy metals, and thermal sprays have an expected lifespan of greater than five years, unless the substrate is coated with a biofilm; the effective lifespan is three years on a substrate coated with a biofilm.

These systems require more review regarding the environmental compliance of the copper leach rates. Copper leaching rates are affected by biofilm development, water temperature, water flow, age and condition of the metal, and other factors. Leaching rates are typically higher after a disturbance or upon initial coating immersion (Wells and Sytsma 2009). Very little information is available on the long-term performance or the copper release rate after long immersion times. In static conditions, the copper release rate is 20 µg cm^{-2} d^{-1}, which is higher than the lower limit of 10 µg cm^{-2} d^{-1}, which is used to gauge antifouling action (Yebra et al. 2003).

5.1.1. Biocide Types

5.1.1.1. Primary biocides

Primary biocides are typically heavy metals, as well as alloys and compounds of metals, such as cuprous oxide. High water velocity, floating debris, or abrasive contact with entrained solids can remove copper-based coatings, allowing foulants to attach in eroded areas. When most of the toxicant is released from the coating or the leaching channels become clogged, the level of cuprous oxide at the surface falls below the minimum necessary to control fouling (Mussalli 1984).

5.1.1.2. Biocide boosters

In an effort to find a suitable antifouling solution for paints without using TBT, companies have developed substitutes able to complement the biocidal action of copper and yield good antifouling properties. Booster biocides, such as herbicides, fungicides, and bactericides are examples of some different substitutes. There are many uncertainties about different environmental parameters associated with booster biocides. Some of these include the environmental profiles of booster biocides; acute and chronic toxicity; validation of analytical methods for biocides, monitoring and fate and toxicity in the environment; synergistic interactions between pollutants; accumulation in the environment; and evaluation of the performance of alternative antifoulants (Yebra et al. 2003).

5.1.1.3. Natural biocides

In natural environments, some organisms remain foul-free, while others become heavily fouled on the surface. The foul-free organisms produce secondary metabolites that may inhibit or repel fouling organisms. The metabolites act enzymatically by dissolving the fouling organism’s adhesive and inhibiting attachment. Examples of the metabolites include fatty acids, steroids, and amino acids. Incorporating natural biocides into paint is currently being studied. Uncertainties with this approach include proving that incorporation of the biocide into paints does not reduce its effectiveness; showing whether the compatible matrix fulfills the same requirements as other paints regarding mechanical properties, stability, and release characteristics; documenting whether large scale production is possible; and production costs (Yebra et al. 2003).

5.1.2. Biocide Containing Paints

5.1.2.1. Self-polishing copolymers (SPC)

SPCs are based on a copolymer binder. Biocides, primarily copper, are attached as pendant groups to the copolymer. SPCs release biocides by hydrolysis or an ion exchange reaction of an acrylic polymer with water. The polymer backbone allows for a controlled and slow release of the biocide (Watermann et al. 2004). When the biocide is released from the hydrophobic SPC copolymers, it leaves a hydrophilic site on the polymer. When hydrophilic sites accumulate, the water-soluble section of the SPC polymer self-polishes by sloughing off, exposing a fresh paint surface (Wells and Sytsma 2009).

In general, only 10-20% of the biocide can be bonded to a copolymer, so the remaining biocides are freely dispersed. The percentage of biocide bonded to a copolymer is not high enough to give the paints effective antifouling properties. Therefore, the products on the market are usually a mixture of SPC and free association paints (Watermann et al. 2004). The lifetime of these coatings depend on its thickness, where thicker coatings tend to last longer. The coatings gradually slough off every year, but a coating thickness of 375μm may last 5 years (Brady 2005).

Examples:
A. International Marine Coatings, Intersmooth Ecoloflex SPC
Ecoloflex SPC is produced by International Marine Coatings. The self-polishing copolymer technology is based on an acrylic matrix bearing copper salts of an organic moiety of unknown composition. The coating has been reported to be active for 3 to 5 years (Yebra et al. 2003).

B. Kansai Paint, Exion
Exion is produced by Kansai Paint. It works through ion exchange, where a zinc-containing pendant group is released from an acrylic backbone. There was no information about the performance after a long immersion time (>30 days) (Yebra et al. 2003).

C. Jotun, SeaQuantum
SeaQuantum is produced by Jotun. It is based on silyl acrylate polymers, which control the release of biocides. Tests of this paint did not show any erosion, but also did not exhibit satisfactory antifouling properties (Yebra et al. 2003).

5.1.2.2. Controlled depletion polymers (CDP)/free association paints
In these paints, the biocide is embedded in a soluble matrix. When the paint surface interacts with water, the paint dissolves, exposing and releasing the embedded biocides (Watermann et al. 2004, Wells and Sytsma 2009). The matrix consists of a binder of rosin-derived compounds and plasticizers or synthetic polymers in which the biocides are dispersed. Rosin is slightly soluble, making it useful in antifouling paints. The polymers give the matrix mechanical strength and film forming properties (Watermann et al. 2004).

The rate of dissolution of the binder is critical for the efficacy of this type of antifouling paint. The soluble matrix facilitates biocide delivery and increases film integrity while it dissolves. Over time, the biocides and the paint mixture wash away because of interactions with impurities and inert molecules in the water, resulting in a leached layer. The leached layer reduces the effectiveness of the paint by inhibiting biocide release which typically limits the lifespan of CDPs to three years (Watermann et al. 2004).

Examples:
A. Military Standard Formula 121/63
This coating has high loading of cuprous oxide and water-soluble rosin. It controls biofouling by continuous contact with copper. This coating is impractical for use in water because its service life is only one to three years and the potential for copper toxicity in the surrounding environments (Mussalli 1988).

5.1.2.3. Self-polishing antifouling/hybrids

These hybrid paints combine the copolymer SPC technology (polishing rate control, control of biocide release, reduced leached layer size) with rosin based CDP technology (surface tolerance and attractive volume solids). Some types of this paint have added booster biocides to enhance the antifouling properties. These paints are effective for three years in dynamic conditions and five years in static conditions (Watermann et al. 2004).

5.1.3. Epoxy Based Paints

Copper/epoxy coatings are composed of a hard, non-ablative epoxy resin that contains metallic copper powder. The copper powder is suspended in an epoxy or polyester matrix and the surface is activated by mechanical means, such as sanding or blasting, that expose the copper particles.

Examples:

A. Epco-Tek 2000

Epco-Tek is composed of an epoxy primer undercoat and successive layers of epoxy mixed with copper powder. It has a lifespan of approximately five years in marine systems. This coating has been studied on concrete, cast iron and fiberglass substrates. The coating is durable and forms a smooth, hard, scratch-resistant, and flexible surface.

Application requires a bare surface to be coated with a low-viscosity 100% epoxy primer undercoat. Five coats of the epoxy-copper coating are then applied. The system is activated by blasting or sanding the topcoat to expose the copper particles. Substrates that were sanded have good fouling protection for the first three years, then fair performance for four years. Substrates that were blasted are well protected for the first three years and had good performance for up to five years. Improper blasting can degrade the coatings performance.

More information is needed regarding the environmental compliance of the copper leach rates of this coating. In a three-year static panel experiment, copper leach rates were between 1.0 and 3.0 $\mu g\ cm^{-2}\ d^{-1}$, but rates as high as 8 $\mu g\ cm^{-2}\ d^{-1}$ have been measured (Wells and Sytsma 2009).

5.1.4. Fluorinated Powder Coatings

Fluorinated powder coatings require shop application and need to be baked on at 500°F in an industrial oven. Therefore, the item to be coated must fit in an industrial oven. Items coated with fluorinated powder were easier to clean, but after one year, fouling was observed (Skaja 2012).

5.2. Biocide Free/Non-Toxic Coatings

Nontoxic coatings were developed to address fouling without leaching a biocide into the water, potentially harming the environment. Nontoxic coatings don’t contain biocides but they do not completely prevent organism growth. The coatings allow for only a weak adhesion between the organism and the substrate. This weak bond causes the foulant to become detached, preventing massive buildups. As a result, the fouling is more manageable, but periodic cleaning and unit outages are still required (Mussalli 1989).

5.2.1. Foul-Release Coatings

Foul-release coatings are considered environmentally friendly. These coatings have two basic mechanisms to protect against fouling; the hydrolysis of polymers which (a) removes fouling with the eroded coating layers and (b) minimizes the initial attachment and strength of the attachment through the properties of the coating surface, preventing or allowing only weak adhesion of the organisms to the surface (Callow 1993, Wells and Sytsma 2009, Nair 1999). In order to adhere to surfaces, fouling organisms synthesize and secrete proteinaceous adhesives that secure them in place. Materials with low surface free energy offer low adhesion strength, resulting in poor attachment (Nair 1999).

Foul-release coatings differ in chemical formulations and the type and amount of free oils and other additives. Many foul-release coating systems require a duplex system, which is multiple layers with different properties applied to the substrate in order to improve adhesion and corrosion protection. A water-resistant anticorrosive layer (epoxy) protects the base substrate and augments the adhesion of the topcoat. Various tie coats bond the tough bottom layer to the hydrophobic topcoat. Catalysts, solvents and curing times improve adhesion (Wells and Sytsma 2009). Most of the topcoats have properties like low surface energy, non-polarity and elasticity, giving the coating a very smooth, slippery, low friction surface. A low surface energy coating has the lowest incidence of fouling. The best low energy surfaces were dominated by closely packed methyl groups and characterized by a surface tension of 22 mN m^{-1} (22 dyne cm^{-1}) (Callow 1993).

Efficacy varies by target species. Hydrophilic surfaces are more effective against proteins and cell adhesion, while hydrophobic surfaces are more effective against macrofouling (Wells and Sytsma 2009). Barnacles and bryozoans tend to foul heavily on low energy surfaces (Callow 1993)

5.2.1.1. Silicone

Silicone elastomer foul-release coatings provide a durable, ultra smooth, slippery, hydrophobic surface. The rubbery nature of silicon causes a weak bond that fractures to help dislodge or remove organisms under flow conditions (Wells and Sytsma 2009). Some silicone coatings contain petroleum oils, which leach out of the coating over time to maintain a slick surface, and enhance the low surface energy characteristics of these coatings. The amount of oils used and thickness of the coating film directly affect the effective service life of the coating (Mussalli 1989). The application thickness of silicone coatings is typically 150 µm. This thicker coating helps control the coating modulus because less energy is required to fracture the bond between the foulant and the coating (Chambers et al. 2006).

Silicone based foul-release coatings appear to function better than fluoropolymers (described in Section 5.2.1.2.), even though fluoropolymers have more mechanical strength. Silicone foul-release coatings are very promising in static and dynamic conditions, but they are soft and not very abrasion or gouge resistant. They have high erosion resistance compared to epoxy coatings for sediment and silt laden waters, but they don’t work as well in areas exposed to heavy debris impacts (Skaja 2012). When tested in seawater, these coating performed satisfactorily for two or more years (Baier and Meyer 1992). Velocity has the effect of shearing off the foulant organism from the coating (Mussalli 1989).

Examples:
A. Chugoku Marine Paints, Bioclean SPGH
Bioclean is manufactured by Chugoku Marine Paints. The film structure combines silicone bonds and methylated groups and does not contain biocides. Bioclean SPGH has been demonstrated to work well against marine and freshwater macrofouling. The coating is fairly durable, but is soft and susceptible to abrasion. The coating has been applied to concrete and steel substrates. Bioclean SPGH 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 works best in flow velocities between 0.9 to 1.2 m s^{-1}. Flows greater than 3.0 m s^{-1} could quickly wear away the coating.

Surface preparation and proper application are important for performance. Improper application can result in coating failures. One case in Texas, the coating delaminated and clogged the facility components. An epoxy primer must be applied first, followed by the silicone topcoat. It is not known if a tie coat or proprietary additives are used to promote adhesion of the coating layers.

The coating has a lifespan of approximately five years on trash and intake bays and seven to nine years on intake tunnels. The difference is likely due to water flow patterns. After one to two years, a small amount of cleaning may be necessary to maintain a low degree of fouling (Wells and Sytsma 2009).

B. Kansai Paint, Biox
Biox, a clear silicone rubber containing an exuding silicone oil, is produced by Kansai Paint. Recoating the substrate every five years is recommended. Biox cannot overcoat itself, therefore reapplication requires water-blasting the rubber topcoat down to the primer, re-priming, and then applying two more coats of Biox.

After one year, marine macrofoulers were able to attach loosely to concrete intake walls coated with Biox. Dewatering the intake bays caused the growths to slide to the bottom, which can then be easily removed. Biox developed more growth over the first two to three years compared to pipes coated with Bioclean. Biox showed no signs of peeling or delaminating except in small areas that were not dried adequately before application (Gross 1997).

C. FujiFilm Hunt Smart Surfaces, Smart Surfaces
Smart Surfaces Duplex Fouling Release system is made by FujiFilm Hunt Smart Surfaces (FHSM). This coating includes epoxy primers, a tethering agent in the epoxy coat to promote adhesion, a tie coat and room temperature vulcanized silicone topcoat that contains proprietary silicone oil. The long-term lifespan is unknown; however, FHSM estimates it to be five years. This coating has been applied to primed steel, aluminum, fiberglass, and concrete substrates. The coating is soft and not considered very durable, however some studies have demonstrated strong durability.

This coating is applied in four coats. The first coat is an immersion grade epoxy primer applied to the bare, clean and dry surface. The second coat is an immersion grade epoxy primer with an added tethering agent. The FHSM tie coat is applied next, followed by the Smart Surfaces topcoat. The minimum substrate surface and ambient air temperatures for application are 4°C and 30% humidity. The maximum ambient air and substrate surface temperature for application are 32°C and 38°C, respectively.

Small scratches to the topcoat damage can be repaired by cleaning the area and recoating. However, damage to the underlying coat or bare substrate requires a new application (Wells and Sytsma 2009).

D. Exsil 2200

Exsil 2200 is a silicone elastomer without exuding silicone oil. When applied over a Plastocor primer to a 3000 ft^2 concrete intake bay, the area was heavily fouled after 2 ½ years. There were also several areas of Exsil that had peeled away from the Plastocor primer (Gross 1997).

E. Adsil, Catalyzed Siloxane Coating

Catalyzed siloxane coatings are produced by Adsil. They are inorganic film formers that adhere by both London force and covalent bond methods to bare non-ferrous metals and concrete. A fully cured film exhibits a slight positive charge, which is hydrophobic and oliophobic, providing a natural repellant against debris. The siloxane film characteristics make it resistant to staining and grime. Microguard AD35, a variety of this coating type, was tested on a push boat. It was applied after the boat had been cleaned and rinsed with PLC-1 and AD72-930, both produced by Adsil. After 2 ½ months, no permanent marine growth was present. These products have not been tested on intake pipes (Ledonne, personal communication, 2014).

5.2.1.2. Fluoropolymer

Fluoropolymers are thermoset polymers based on compounds made from carbon bonded to fluorine. This type of coating is thinner and harder than silicone with more mechanical strength (Wells and Sytsma 2009). The application thickness of fluoropolymer coatings is 75 µm (Chambers et al. 2006). These coatings have a well-organized surface of tightly packed fluorinated groups that lowers the surface energy. They also have a high modulus, which requires greater force for interfacial fracture, which occurs by shear (Brady 2005).

Examples:

A. International Marine Coating and Nippon Paint, Intersleek 970

Intersleek 970 is used in the Intersleek 900 foul-release system manufactured by International Marine Coating and Nippon Paint. The Intersleek 900 system includes an anticorrosive primer layer (Integard 264), a tie coat layer (Intersleek 731) and the finish coat (Intersleek 970). The system has primarily been applied to metal, and it is not known if the system could be applied to concrete. The system is resistant to direct impact but is susceptible to mechanical damage such as gouging or scraping activities

Proper application is critical for the coating to work properly. The substrate surface must be at least 3°C above dew point and between 21°C and 27°C for optimum application. The average life span is five years. The long-term performance is unknown, but the system does well in short-term performance. After a six month exposure period in marine waters, over 64% of the coated surface was free of macrofouling in static conditions, and 97.4% was free of macrofouling in dynamic conditions (Wells and Sytsma 2009).

5.3. Summary

Coatings based on foul-release paints are effective and limit initial settlement and attachment. However, these systems are mechanically weak and subject to failure due to detachment and abrasion. Biocide-based coatings are effective and strong, but release toxins into the surrounding environment, which may impact surrounding organisms.

All of the coatings need to be applied to clean, dry substrates. The piping system must be shut down for a minimum of four days to accomplish coating application. Both types of coating systems require the pipes to be cleaned periodically in order to maintain a low level of fouling. Also, the coatings require periodic reapplication, which can take several days depending on the coating type and degree of wear or damage.

6. Mechanical Approaches

Mechanical cleaning of intake pipes consists of two primary categories: online and offline. Online techniques clean the system without removing it from service. Examples of this technique include ball systems, metal scrappers, and brush and cage systems (Nair 1999, Rice et al. 1993). Offline techniques clean the system during scheduled outages. Examples of this technique involve shooting or lancing (Rice et al. 1993). This cleaning procedure and frequency varies greatly depending on debris type and loading.

6.1. Online

The method used for a given site depends on the level of biofouling, space available for filters, ball strainers or cages for brushes, and availability of reverse-flow capability. This method typically removes a thin layer of the foulant with each cleaning, so foulants are not able to build up (Rice et al. 1993). This cleaning method is able to take place while the plant is in operation.

6.1.1. Ball Systems

6.1.1.1. Overview

Ball systems operate by using the cooling water flow to push or force slightly oversized sponge rubber balls through the condenser pipes, continuously wiping the inner pipe walls (Rice et al. 1993). After flowing through the pipes, the sponge balls are captured by special strainers or filters (Cristiani 2004). Some plants use the ball cleaning system continuously while others prefer to use it a few times a week or during an emergency. Cleaning with sponge balls reduces or eliminates the need for chemicals.

Different balls are available to remove different foulant types. Standard balls are used in general applications and come in a variety of sizes and hardnesses. Extended life balls are made of standard balls coated with a smooth skin which wears out over time, resulting in an extended life. However, the smoothness reduces cleaning efficiency, so they are only recommended for mild fouling issues. Abrasive balls are recommended for harsh conditions or pipes with strongly attached foulants. They are made by coating or blending the standard balls with an abrasive material (Leung et al. 2002, Rice et al. 1993).

Undersize balls do not clean as effectively and need to be removed regularly. The system needs to be shut down to remove undersized balls and pass through a clearance check. An operator sizes the balls at the clearance check and removes undersized or worn out balls, which can require several hours of their time. Another option is to replace the entire ball stock without sizing, based on average ball lifetime (Rice et al. 1993). Most manufacturers recommend completely replacing a set of balls once a month, however past data indicates that complete replacement frequency is actually higher (Rice et al. 1993).

Effective cleaning using sponge balls depends on even flow distribution in the condenser. If the flow is uneven, the balls may not be uniformly distributed, which leads to inadequate cleaning or excessive wear in some pipes. Over-cleaning may remove any protectant-coating while under-cleaning may leave a foulant film or other materials (Rice et al. 1993).

The sponge ball cleaning system can be negatively affected by debris. If the pipes or strainers become clogged with debris, the sponge balls can also become stuck and further clog the system making it useless (Rice et al. 1993, Perkins et al. 2009). Clogging will change the differential pressure in the strainer section, so an automatic backwash system is recommended to clean the screen when the differential pressure reaches a certain setpoint.

The strainer design is critical for proper operation. If the strainer fails, balls can escape (Perkins et al. 2009, Rice et al. 1993). In 2003, Calvert Cliffs accidently discharged approximately 400 pounds of balls into the Chesapeake Bay over a 75-d period and was in violation of their NPDES permit (Nietmann 2003). Some strainers with multiple screens and linkages require an average of 15 hours per month to repair linkages and performance maintenance. Other strainers require minimal maintenance (Rice et al. 1993).

Ball cleaning systems are marginally effective. The ball systems assist in keeping the system clean and greatly reduce, but do not eliminate the need for manual cleaning. Some facilities must backwash their system during heavy debris loading to clean debris from the filters and strainers. The potential operating and maintenance costs can be high (Perkins et al. 2009).

6.1.1.2. Cleaning process

Cooling water is first moved through a debris filter to remove coarse solids. The three steps followed during cleaning are described below.

A. Ball injection

Balls are inserted into circulating water upstream of the condenser inlet, against the direction of the inlet cooling water flow. The balls are the same density as the cooling water when deaerated, allowing the balls to enter the pipes randomly. A charge of balls equal to 5 – 15% of the number of condenser pipes per pass should maintain cleanliness.

B. Pipe cleaning

Ball distribution is affected by the location of the ball injection and flow patterns in the inlet waterbox. Backwashing starts automatically once the differential pressure across the debris filter and strainer reaches a preset limit.

C. Ball collection and return for inspection
The balls are collected at the outlet by a strainer then redirected by a recirculating pump to the ball collector. At the collector unit, operators must then visually inspect the balls, manually size them and replace any undersize balls. Balls flow from collector unit to the injection location at the inlet water box where cycle begins anew (Leung et al. 2002, Rice et al. 1993).

6.1.1.3. Retrofit considerations

When installing a ball cleaning system into an existing piping system, space and outlet piping configurations can impact the retrofit. If a debris filter has not already been installed, this should be considered, as it can be costly to install. The ball collection strainer requires accessible exposed piping of one pipe diameter at the outlet, therefore the outlet pipe's location and design can affect the ball collection strainer and the retrofit costs. The remaining system components (valves, pumps, etc.) can be installed where space is available. The location and number of ball injectors required to achieve uniform ball distribution in the pipes is affected by inlet piping and waterbox design, and the resultant hydrodynamics (Rice et al. 1993).

The start-up costs for using the ball cleaning system are lower than other online options as it only requires a ball addition and ball collection system. However, the piping systems require adjustments to the mechanized control system components and controls. Space and piping configurations can also influence the retrofit (Rice et al. 1993).

6.1.2. Brush and Cage Systems

This system is used primarily by smaller power plants, although some large power plants do use it. This system uses a flow-reversal mechanism to shuttle a captive brush back and forth through each pipe by reversing the flow direction. The cleaning brushes are caught by nylon cages attached to the end of the pipes with epoxy and screws.

The brush and cage system requires limited maintenance or operator attendance. The only moving parts are the flow reversal valves and brushes, so the worn cleaning elements do not need to be replaced frequently. The lifetime of the brushes is approximately 5 years. The system provides continuous cleaning without the need for chemicals (Rice et al. 1993).

The flow-reversal system is expensive and can increase back pressure, reduce generator output and hydraulic transients in the system. The system must be shut down during brush and cage replacement. The cages obstruct the ends, making it difficult to detect pipe leaks and conducting eddy current tests. The cages can become clogged with debris if a filter isn't installed. The brushes may over-clean the pipes, remove pipe material, or can become bent or damaged thus restricting pipe flow (Rice et al. 1993).

6.2. Offline

Offline pipe cleaning involves shooting or lancing. Shooting propels a tube-cleaning projectile (plastic pig) through each pipe using pressure, while lancing pushes and pulls a flexible lance or rotating shaft with an attached cleaning device (water head, brush, scraper, drill bit or cutter) through each pipe. Shooting requires moving an object through the pipes at speeds of 10-20 ft s^{-1} and is faster than lancing. Lancing requires manual feeding and withdrawal of the lance. The most common types of offline cleaning equipment are pressure-driven systems (water lances and air/water systems (brushes, pigs, scrapers, air/water)) and mechanical systems (scrapers, cutters, rotating brushes). The method for each site depends on the rate of corrosion and biofouling; physical characteristics and corrosion resistance of the pipe material; type of foulant; length of unit outage; and cleaning frequency (Rice et al. 1993).

Offline systems cost less than online and require little maintenance or monitoring. All offline systems require an operator or technician to operate. The condenser or section of the condenser must be taken out of service to access pipes, and the piping system must be shut down. When the offline cleaning is completed, the system is put back in service and the cleaning components are stored.

Offline systems are typically only used when the foulant has built up enough to warrant shutdown. A heavily fouled area may be challenging to clean. Brushes are only effective at cleaning soft foulants, scrapers are too slow to use for routine cleaning, and pigging can damage pipe walls and/or become jammed (Stone and Webster Engineering Corp. 1992).

6.2.1. Pressure Driven Systems

6.2.1.1. Flushing/water lances

Flushing requires forcing water through the pipes at high speeds to carry away particles. This method requires a large volume of water that is pumped through a flexible hose or metal shaft with a stainless steel head attached at the end. The head has several holes drilled into it to define a particular spray pattern and self-propel water through the pipe. Water pressure of about 8,000 to 10,000 psi is used, so operators need to use extreme caution. The high pressure can collapse pipe ends and inserts and damage the pipe coatings. Equipment being cleaned must be taken out of service in order to operate the lance. The lances can damage and gouge the pipes if used aggressively or incorrectly (Rice et al. 1993).

6.2.1.2. Air/water systems

One of the simplest systems uses a cleaning brush that is blasted into the pipe using compressed air, pressurized water (approx. 200-400 psi), or both. Debris is flushed out with propellant as the brush moves along the pipe and into the outlet waterbox. Scrapers must be used when the foulant cannot be removed by the brushes (Rice et al. 1993). Scrapers are described in Section 6.2.2.

Pigging requires forcing an object (pig) through the pipe to push or wipe away loose material. This method requires building launch stations and receiving stations. Inline valves, meters, or other structures in the flow path may block the pig. The devices do not require special maintenance or monitoring; however there is immediate performance degradation after cleaning. Pigs are typically cheaper than online alternatives, but the labor costs are higher because they require an operator or technician to operate. Pigs have been designed to be self-propelled for use in longer runs of piping and for areas with 90-degree bends. Pigs are able to use terminal points (e.g., valves) to activate a reverse mechanism to change travel direction. Pigs can also take advantage of oncoming velocity head to propel themselves upstream (Stone and Webster Engineering Corp. 1992).

6.2.2. Mechanical systems

Cutters and scrapers are used to remove difficult foulants. Cutters come in a variety of configurations and most are equipped with flexible shafts or universal joint shafts. Equipment being cleaned must be taken out of service in order to operate the cutter. The cutters can damage and gouge the pipes if used aggressively or incorrectly. Cutters are also significantly slower than other o cleaners (Rice et al. 1993).

Scrapers match the pipe diameter, and operate by using spring loaded scraping edges to clean the pipes. Equipment being cleaned must be taken out of service in order to operate the scraper. The scrapers can damage and gouge the pipes if used aggressively. If the foulant buildup is thick and hard, high-pressure water lancing equipment also needs to be used (Rice et al. 1993).

6.3. Debris Filters

Inline strainers/debris filters installed between the water source and the condenser inlet waterbox or other heat exchangers have been used to reduce debris. Debris filters remove material that has passed through preliminary and secondary screening technologies or has originated within the piping (Stone and Webster Engineering Corp. 1992). Filter types available in the US include turbulence, waterbox, backwash, and inline debris separator. Most of the filters used in the US are the backwash design and intended for automatic operation.

In the turbulence filters, water and debris enter the annulus between the cylindrical screen filter basket and screen housing. During flushing mode, tangential flow created by inlet valve action removes the debris from the filter element. The debris is flushed into a discharge pipe. This type has some difficulty flushing off heavy debris influxes and stringy debris (Stone and Webster Engineering Corp. 1992).

The backwash filter uses four separate basket sections that sequentially close off cooling water flow and backflush during flushing mode. Debris is removed from the baskets by flushing clean (filtered) water through and carrying it to the discharge pipe (Stone and Webster Engineering Corp. 1992). The strainer screen rotates a section of the screen to a position where a stationary suction scoop pulls debris off the strainer mesh. Strainers may not improve operating water levels for the circulating water pumps and may not perform adequately during periodic algal loading events. These filters work well in areas where biofouling is occurring in the piping downstream of the circulating water pumps (Perkins et al. 2009). More research is needed to reduce head loss associated with these filters.

Waterbox and inline debris separators use conical strainers with external rotating jet spray at the clean water side. The jet spray transfers debris from the strainer surface to the cone tip, cleaning the filter surface. Periodically, debris is flushed through the debris discharge manifold.

Filters have some disadvantages. System head (pressure) loss increases approximately 1.5 ft. with clean filters and 2 ft. when the filters are 30% fouled (water velocity 9 ft. s^{-1}). When the filters are retrofitted to an existing system the system pressure must be increased thus increasing station pumping costs. If the intake pipe cannot be adjusted to compensate for the pressure drop, the unit is not able to run efficiently and the cooling water flow drops. These filters work best when used with another type of pipe cleaning system (Stone and Webster Engineering Corp. 1992).

6.4. Summary

Online systems clean a thin layer of foulant with each pass, so organisms are not able to build up. There is limited maintenance and operator attention required and service is usually not interrupted during cleaning. Constant movement of the balls in the pipes can deteriorate pipe wall material and brushes can scrape away the wall material as well. Balls must be inspected and replaced frequently. Debris can stop ball movement, causing the pipes to clog, resulting in a system shutdown.

Offline systems provide a variety of options to deal with either soft foulants, or harder and tighter foulants. The water lance system is the only method that does not require periodic replacement. All offline systems require an operator during cleaning. Some equipment poses safety hazards due to the high water or air/water pressures that are used to move the mechanism through the pipe. The cleaning materials used can damage pipe walls if used aggressively or incorrectly (Rice et al. 1993).

Pipe cleanliness may begin to deteriorate as soon as the cleaning is complete. If a hard fouler is attached in the pipe, the mechanism may not be able to adequately remove it (Rice et al. 1993). There is a loss of production if the system requires the plant to be shut down. Once the plant is brought back into operation, the foulants will continue to grow back, decreasing the plant's efficiency.

7. Combination Approaches

The descriptions of biofouling control options provided above include approaches that that can be considered combinations (e.g., use of sodium hypochlorite plus sodium bromide) and the case studies below provide additional examples (e.g., copper and chlorine). Beyond simple chemical mixtures, combinations of a targeted mechanical, coating, or water treatment strategy have the potential to enhance or optimize cooling system fouling control. For example, as described in Section 2, a combination of heat and acetic acid has been proposed to specifically control hydroids. However, all potential combination strategies require careful consideration of the benefits gained from multiple approaches against the added costs and logistical constraints associated with more than one control measure.

A combination strategy employed by some power plants is to install debris filters to remove coarse solids and large organisms and water treatment (e.g., chlorination) or an anti-fouling coating. However, very little information is available on the performance and costs of these combined approaches. CCNPP has decided against debris filters as a control strategy but has applied a silicon-based anti-fouling coating, which appears effective at limiting the growth of many macro-organisms but does little to control *G. franciscana*. Additionally, the aging, maintenance and reapplication of the coating has become a concern. The addition of a water treatment and/or online mechanical approach to the existing anti-fouling coating strategy may be more successful at controlling the problems associated with *G. franciscana*, but the biocides and cleaning approaches used can negatively impact coating performance by increasing wear.

While the ultimate goal is to effectively control the problems associated with growth of *G. franciscana* and other fouling organisms in the CCNPP cooling systems, any single or combination strategy must not impact fundamental plant operations and must be cost-effective. As approaches are added to a fouling control strategy, typically overall complexity, and thus potential for failures, and costs will increase.

8. Case Studies

8.1. Surry Nuclear Power Plant and *G. franciscana*

Surry Nuclear Power Station (on the James River in Surry, VA) conducted a study with the Virginia Institute of Marine Science and Stone and Webster Engineering Corporation in 1992 to help establish a fouling control program (Stone and Webster Engineering Corp. 1992). Like CCNPP, the major contributing macrofoulers were hydroids during spring, summer and fall, with *G. franciscana* identified as the primary species of concern. Other macrofouling organisms, including bryozoans, crabs and barnacles, were also found within their cooling water systems.

Similarly, the problems related to fouling included reduced flow, increased traveling screen component failure rates, increased corrosion rates, condenser inlet tubesheet fouling, and heat exchanger inlet tubesheet fouling. Almost daily cleaning was needed during the late spring through early fall periods. The final report reviews and summarizes methods used or tested to control biofouling in various power plants prior to this 1992 study, including coatings, electrical current/cathodic protection, mechanical, thermal backwash, physical methods including UV, ultrasounds and acoustics, non-toxic chemicals, freshwater injection, magnetic treatment, robotics, high water velocity, biological control, chemical treatment, and asphyxiation. Of these, mechanical, coatings, chemicals and asphyxiation were considered and tested for the Surry plant.

8.1.1. Recommendations

The existing "traveling screens" required upgrades to increase efficacy. The spray wash system in place at the time did not produce enough pressure to be effective in cleaning fouling off of the traveling screens because fouling in the pressure lines had reduced pressures from 80 psi to 15 - 20 psi. Specific upgrades recommended for the traveling water screen (TWS) system included: TWS units with forward and reverse speeds sufficient to dislodge jams; TWS hoods for spray observation with hood heaters for winter use; and basket lips to remove larger objects (e.g., carcasses, shells).

It was also recommended to coat specific areas with Bioclean or another silicone-based foul-release coating. There were concerns about the coating falling off in sheets if used on the downstream side of the screens because failure rates had not been tested.

Water treatment options including deoxygenation were also considered, but it was concluded that anoxia, as opposed to hypoxia, must be achieved to be effective in controlling *G. franciscana*.

While anoxia could be achieved by chemical injection, other options, especially biocide water treatment, appeared more likely to succeed and be cost-effective.

The injection of sodium hypochlorite, ammonium hydroxide, hydrogen peroxide, Acti-Brom (sodium bromide) and ClamTrol-CT1 were considered and tested with mixed results. Bulk and continuous chemical treatment was deemed infeasible for any of the biocides considered and for chlorine-based water treatment (e.g., sodium hypochlorite). The EPA allows a maximum concentration of free available chlorine of 0.5 mg L^{-1} and average concentration of 0.2 mg L^{-1} with only one unit discharging for a maximum time of 2 hours per day, unless the utility can demonstrate to the Regional Administrator or State (if the State has NPDES permit issuing authority) that the units in a particular location cannot operate at or below this level of chlorination (40 CFR 423.12 (8)). At these allowable concentrations, hydroids were damaged but regrew in laboratory experiments (Stone and Webster Engineering Corp. 1992). However, spot or pulsed sodium hypochlorite treatment at higher doses in specific areas was deemed feasible and could be effective. A "wet layup" procedure including a "chemical injection skid to provide corrosion control" was advised for pipes that were alternatively wet as hydroids grew, then dry as hydroids die, then wet again as hydroids break off in the flow and clog systems.

8.1.2. Status of Biofouling Control

The Surry Nuclear Power Plant has had success controlling *G. franciscana*, and waterbox biofouling in general, using a chemical treatment supplied by NALCO. The treatment is based on liquid injection of sodium hypochlorite (13% specified but actually closer to 10% by the time it is used) and Acti-Brom (43%) using two one-hour injection times each day. The flow rates of injection are 300 gal sodium hypochlorite and 70 gal Acti-Brom pumped into the four cooling water pipe intake cavities, twice a day, per unit. Chemical flow rates are based on the power plant's circulating water flow rate of 52,000,000 gph with a total daily chemical usage of 1,200 gal of sodium hypochlorite and 280 gal of Acti-Brom.

A similar approach implemented at CCNPP would require larger volumes of injected chemicals. Surry has four cooling water pipes per unit that pump 220,000 gpm each with a total flow per unit of 880,000 gpm, and a total site flow rate of 1,760,000 gpm. CCNPP has six cooling water pipes per unit that pump 200,000 gpm each with a total flow per unit of 1,200,000 gpm and a total site flow rate 2,400,000 gpm. The supply, delivery and handling of such large amounts of concentrated biocides could present significant cost, logistical and safety concerns. However, a similar dose and application approach can be achieved by on-site generation of sodium hypochlorite through electrolysis (i.e., electrochlorination), and if bromide salt levels in ambient cooling water at CCNPP are naturally high enough, the addition of Acti-Brom may not be necessary to achieve comparable results.

If this or any other approach is to be implemented, all cooling water system components must be mechanically cleaned or the treatment could cause significant sloughing of existing fouling organism, which could clog the system and trip individual units.

8.2. Biofouling and its Control in Power Plant Cooling Water System – Satpathy et al. (2010).

8.2.1. Overview

Satpathy et al. (2010) provides the most recent and comprehensive overview of biofouling and its control in power plant cooling water systems as a chapter of the book entitled *Nuclear Power* (2010). An introduction/overview of biofouling in power plant cooling systems and how biofouling growth affects the intake water needs of power plants is provided. Satpathy et al. (2010) describes the economic impacts of biofouling, bio-growth in different sections of a cooling water system, biofouling and safety consequences of nuclear power plants, and events that could exacerbate fouling.

8.2.2. Fouling Case Study

An in-depth study at the Madras Atomic Power Station (MAPS) was chosen as a case study to understand the biofouling problems in a typical seawater cooled power plant whose systems have been studied in great detail. MAPS is located on the Kalpakkam coast (Bay of Bengal) and has significant seasonal biofouling challenges, including two hydroid species *(Obelia biontata and Obelia dichotoma*) that were second only to barnacles in abundance.

Selection of a suitable biofouling control strategy, particularly the chemical control methods, for a cooling water system depends upon the physicochemical properties of the cooling water itself. Biofouling control methods can become inefficient due to the ability of the fouling organisms to alter the chemistry of the cooling water themselves. Thus, continuous monitoring of the cooling water at the outfall discharge is as important as that of the intake water to find out the efficiency of the control method. This is true for biocides in particular. For example, an increase in pH and turbidity and a decrease in DO levels was noted in the MAPS forebay samples as compared to that of the intake. Using hydrography and biofouling data, a study was designed and carried out to assess the impact of the activities of the fouling community on the physicochemical properties of the cooling water at MAPS to assess any possible interference in the operation and maintenance of the cooling water system.

Satpathy et al. (2010) concluded that although methods like Amertap, spongeball, screens of various sizes, heat treatment and different biocides are in use for prevention and control of biofouling, chlorination stands out as the most widely used and efficient method owing to its proven effectiveness, easy availability and relatively low cost for the chlorination of cooling water. The authors estimated that electrochlorination (on-site/in-line production of sodium hypochlorite) is one of the most cost-effective approaches to the use of a biocide in power plant anti-fouling. Electrochlorination is about half the cost of the injection of liquid sodium hypochlorite, and far less expensive than other common oxidants such as ozone. However, recently implemented EPA and state limitations described above must also be taken into account.

MAPS is similar to the majority of power plants in that the fundamental biofouling control strategy selected for use is based on chlorination, with MAPS specifically using sodium hypochlorite. However, chlorine demand values vary with location and season and should be quantified to help optimize the process and to ensure that under- and over-dosing are prevented.

8.2.3. List of Control Strategies Reviewed

Satpathy et al. (2010) discuss the following control strategies and provide a few conclusions:

A. Physical methods – Physical methods are screens and sieves that can be used to prevent entry of macro-organisms or larger, but will not prevent micro-organisms or larvae from entering cooling water systems.

B. High flow velocity – Using a high flow velocity only works if velocity remains constant and hydrodynamic conditions prevent the settlement and/or attachment of fouling organisms. However, once organisms are attached, high flow often does not prevent their growth.

C. Heat – High water temperatures can prevent or minimize fouling. For example, temperatures of 40°C for one hour can kill many bivalves, but heating water in the cooling water system is energy intensive and will interrupt normal flow.

D. Mechanical methods – These methods have not been popular because they are only useful for microfouling control in the condenser section, interrupt normal cooling water flow, and can be cost prohibitive.

E. Osmotic control – Osmotic control by varying salinity can work on marine or freshwater organisms if it is possible to greatly manipulate salinity.

F. Bromine-based compounds – Bromine chloride has been used to control fouling because the biocide: (a) has rapid residual decay and lower potential for condenser corrosion rates, (b) has high solubility, (c) has a high density that permits a large mass of liquid BrCl to be supplied in a small container, (d) works under broad temperature and pH ranges, and (e) may be more economical when the cost of maintaining EPA regulation of discharge limit is taken into account.

G. Ozone – Ozone is a common fouling prevention approach but limitations include: (a) difficulty to achieve uniform distribution, (b) ozonizer occupying large space and necessity for on-site generation, and (c) high costs typically restrict the use of ozone largely for treatment of potable water and sewage. Moreover, there is very little information available on the possible corrosion of condenser tubes. Like chlorine, ozone is also is affected by pH, temperature, and organics.

H. Bioactive compounds – A variety of other compounds have been considered and discussed (e.g., iodine, hydrogen peroxide, potassium permanganate, and chlorine dioxide) but Satpathy et al. (2010) concluded that they are still experimental and that extensive additional research is needed.

I. Antifouling coatings – Various coating options are available utilizing organometallic compounds and copper oxide. Copper has not been popular due to high cost, operational difficulty and short life span. Acrolein is an effective antifouling agent, but it is expensive, highly toxic and also highly flammable. Non-stick or silicon based coating were discussed briefly.

J. Ionizing radiation – The adverse effects of ionizing radiation on biological systems have been evident since its discovery, and attempts have been made to introduce radioactive materials into antifouling coatings. Studies carried out using thallium-204 radioisotopes demonstrated the significant antifouling capability of this material. However, the dosage required (20 rads h^{-1}) was considered too high for comfortable handling by untrained operators. Nuclear power plants, which have highly trained operators in handling radioactive materials, could consider this as a viable technique for control of biofouling.

K. Chlorination

Electrochlorination – For safety and cost reasons, electrochlorination has become more widely used for power plant fouling control. Though some safety problems are eliminated in electrochlorination, environmental safety concerns and restrictions remain, with the addition of a significant capital equipment investment and equipment maintenance. Electrochlorination produces hydrogen gas, which must be handled/vented appropriately.

Exomotive chlorination – To overcome the problem of biofouling, long-term low-level continuous chlorination is usually used. Such a practice is also effective in the control of condenser slime. This method was originally started at Carmarthen power station in the U.K. The dose employed is insufficient to kill mussels but sufficient to create an environment to deter them from settling in the cooling water system and to cause them to move out, hence the term exomotive chlorination. Exomotive chlorination is found to be economical and relatively harmless to important nontarget commercial organisms.

Copper and chlorine – A recent successful use of a combination of copper and chlorine has been reported by both CEGB and EPRI. Results of both showed that the chlorine and copper system was at least six times as effective as chlorine alone against macrofouling and three times as effective against microfoulants.

Pulsed chlorination – Periodic chlorination shock, with high doses has also been found to be an effective approach at killing or controlling most fouling organisms.

8.2.4. Summary

Although alternative biocides are available, sodium hypochlorite still remains the most common method for biofouling control in cooling water systems and is often preferred to others because of its proven effectiveness, easy availability and relatively low cost.

Three basic considerations should be kept in mind when employing chlorine, irrespective of its source: (a) safety associated with production, transport and/or storage, (b) potential threat to marine life, and (c) the variability in chlorine demand based on water temperature, salinity, and organic load should be addressed to optimize the process. Intermittent or pulsed chlorination can also be very effective if optimized and properly monitored.

9. References

Abbe, G.R. 1987. Epifauna, In: Heck, Kenneth L. (Eds). Ecological studies in the middle reach of Chesapeake Bay- Calvert Cliffs. Berlin. Springer-Verlag. p. 82-91.

Baier, R.E. and A.E. Meyer. 1992. Surface analysis of fouling-resistant marine coatings. Biofouling. 6 (2): 165 – 180.

Brady, R.F. 2005. Fouling-release coatings for warships. Defense Science Journal. 55 (1): 75-81.

Calder, D.R. 1990. Seasonal cycles of activity and inactivity in some hydroids from Virginia and South Carolina. U.S.A. Canadian Journal of Zoology. 68(3): 442-450.

Callow, M.E. 1993. A review of fouling in freshwaters. Biofouling. 7 (4): 313 – 327.

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

Cory, R.L. 1967. Epifauna of the Patuxent River Estuary, Maryland, for 1963 and 1964. Chesapeake Science. 8: 71-89.

Cristiani, P. 2004. Solutions to fouling in power station condensers. Applied Thermal Engineering. 25: 2630 – 2640.

Crooks J., A. Chang and G. Ruiz. 2011. Aquatic pollution increases the relative success of invasive species. Biological Invasions. 13:165–176.

Crowell, S. and R.M. Darnell. 1955. Occurrence and ecology of the hydroid *Bimeria franciscana* in Lake Pontchartrain, Louisiana. Ecology. 36(3): 516-518.

Davidson, I., G. Ruiz, M. Sytsma, P. Fofonoff, B. Mohammad, L. McCann, C. Zabin, and S. Altman. 2007. A post-voyage analysis of hull biofouling on the vessels Point Loma and Florence after transit from California to Texas. Report submitted to the U.S. Maritime Administration, Washington D.C.

de Rincon, O., and B. Morris. 2003. Studies on selectivity and establishment of "Pelo de Oso" (*Garveia franciscana*) on metallic and non-metallic materials submerged in Lake Maracaibo, Venezuela. Anti-Corrosion Methods and Materials. 50: 17-24.

Environmental Protection Agency Science Advisory Board. 2011. Efficacy of ballast water treatment systems. EPA-SAB-11-009.

Fofonoff P.W., G. Ruiz, B. Steves, and J.T. Carlton. 2003. National Exotic Marine and Estuarine Species Information System. http://invasions.si.edu/nemesis/browseDB/SpeciesSummary.jsp?TSN=48820

Gross, A.C. 1997. Long-term experience with non-fouling coatings and other means to control macrofouling. In D'Itri, F.M. Zebra mussels and other aquatic nuisance species. Boca Raton, (FL) CRC Press LLC. p. 329-342.

Guenther, J., I. Fitridge and E. Misimi. 2011. Potential antifouling strategies for marine finfish aquaculture: the effects of physical and chemical treatments on the settlement and survival of the hydroid *Ectopleura larynx*. Biofouling. 27(9):1033-1042.

Ledonne, B. 2014. S&S Interiors, personal communication.

Leung, M., L. Godwin, W.H. Chan, J.Y. Qin, and S.Y. Lee. 2002. Sponge-ball automatic cleaning device for saving energy in a chiller. International Energy Journal. 3 (1): 35 – 43.

Lippson, A.J. and R.L. Lippson. 2006. Life in the Chesapeake Bay. Baltimore, (MD). Johns Hopkins University Press.

Lloyds Register. 2010. Ballast water treatment technologies: Current status. www.lr.org/Images/BWT0210_tcm155-175072.pdf.

Mussalli, Y.G. 1984. Condenser macrofouling control technologies. CS-3550. Research project 1689-9. Prepared for Electric Power Research Institute.

Mussalli, Y.G. 1988. Biofouling control at water intake structures. Journal of Hydraulic Engineering. 114: 616 – 625.

Mussalli, Y.G. Stone & Webster Engineering Corporation.1989. Nontoxic foul-release coatings. GS-6566, Research project 1689-9. Prepared for Electric Research Power Institute.

Nair. K.V.K. 1999. Marine biofouling and its control with particular reference to condenser-cooling circuits of power plants – an overview. Journal of Indian Institute of Science. 79 (Nov-Dec): 497 – 511.

Nietmann. K. 2003. Constellation Energy Group, Calvert Cliffs Nuclear Power Plant. Letters to US Nuclear Regulatory Commission and Maryland Department of the Environment regarding discharge of sponge balls into the Chesapeake Bay.

Perkins, N., E. Matys, N. Olken, and G. Allen. 2009. Alden Research Laboratory, Inc. Best management practices manual for preventing cooling water intake blockages. I.D. 1020524. Final Report. Electric Power Research Institute.

Rice, J.K., J. Garey, Y.G. Mussalli, and P. Puckorius. 1993. Condenser microbiofouling control handbook. RP. 2300-16. Final Report, TR-102507. Prepared for Electric Power Research Institute.

Satpathy, K.K. A.K. Mohanty, G. Sahu, S. Biswas, M.V.R. Prasad and M. Selvanayagam. 2010. Biofouling and its control in seawater cooled power plant cooling water system - A review, Nuclear Power, Pavel Tsvetkov (Ed.) ISBN: 978-953-307-110-7. In Tech, available from: http://www.intechopen.com/books/nuclear-power/biofouling-and-its-control-in-seawater-cooled-power-plantcooling-water-system-a-review.

Skaja, A. 2012. Coatings for mussel control – three years of laboratory and field testing. Technical Memorandum No. MERL-2012-11. U.S. Department of the Interior. Bureau of Reclamation.

Schuchert, P. 2007. The European athecate hydroids and their medusae (Hydrozoa, cnidarian): Filifera Part 2. Revue Suisse de Zoologie. 114: 195-396.

Stone and Webster Engineering Corporations. Solutions to macrofouling in the service water system, Surry Nuclear Power Station, 1992. VARK32.B7S.

Theede, H., N. Scholz and H. Fischer. 1979. Temperature and salinity effects on the acute toxicity of cadmium to *Laomedea loveni* (Hydrozoa). Marine Ecology Progress Series. 1:13-19.

Thompson, M. L. 1993. Dynamics of an oligohaline, macrofaunal, fouling community. M.S. Thesis, College of William and Mary, Williamsburg VA. Pp.

Torrey, H. B. 1902. The hydroida of the Pacific Coast of North America. University of California Publications. Zoology. 1:1-104

Venkatesan, R. and P.S. Murthy. 2008. Macrofouling control in power plants. In the Biofouling and Biofilm Processes Section, Water and Steam Chemistry Division, BARC Facilities, Indira Gandhi Center for Atomic Research Campus, Kalpakkam , 603 102, India, Springer Series on Biofilms. Pages 265-291.

Vervoort, W. 1964. Note on the distribution of *Garveia franciscana* (Torrey 1902) and Cordylophora caspia (Pallas, 1771) in the Netherlands. Zoologische Mededelingen. 39: 125-146.

Wells, S. and M. Sytsma. 2009. A review of the use of coatings to mitigate biofouling in freshwater. Prepared for the Bonneville Power Administration and the Pacific Marine Fisheries Commission.

Watermann, B., L. Weaver, and K. Hass. 2004. Feasibility study for new eco-labels according to DIN EN ISO 14024 for select product groups. Sub-project 3: Biocide-free antifouling products. Research Report 201 95 311/02 UBA-FB 000698e. Environmental Research of the Federal Ministry of the Environment, Nature Conservation, and Nuclear Safety.

Yebra, D.M., S. Kiil, K. Dam-Johansen. 2003. Antifouling technology – past, present, and future steps towards efficiency and environmentally friendly antifouling coatings. Progress in Organic Coatings. 50:74-104.

Zammit, 2013. Controlling Hydroids from Hell (*Garveia*) at the Entergy Sabine Plant, PowerPoint Presentation.