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Marine biofouling and its control with particular reference to condenser-cooling circuits of power plants — An overview

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Abstract

Biofouling has been a major problem to ships, offshore platforms, marine intakes, data buoys and to almost all marine-technology ventures. With the emergence of multi-megawatt power plants during the last three decades more and more nuclear and thermal power stations are turning to the sea to meet their cooling water needs. The use of sea water for condenser cooling has brought the problem of marine biofouling into power-plant intake and discharge conduits as well as heat exchangers. The problem is particularly severe in tropics and even more so in ocean thermal energy conversion (OTEC) plants wherein the sea water flows through evaporators as well as condensers. While many approaches are followed for control of biofouling involving chemicals, antifouling paints, foul-release coatings, electric charges, velocity and heat, there is no method which can totally prevent it. The paper reviews the state of the art in this area largely based on experience from a power station at Kalpakkam, south of Chennai.

Keywords: Marine biofouling, power plants, OTEC cooling circuits, fouling control.

1. Introduction

Biofouling refers to the colonization and growth of fauna and flora, either marine or freshwater, on man-made structures. Biofouling affects all maritime operations, be it shipping, offshore oil mining, coastal power generation, marine electronics, mariculture, marine construction or naval operations. The problems encountered are many as are the number of species involved.[1] Relini[2] provided a brief list of marine structures needing protection against biofouling. It includes ship and submarine hulls, sea-water intakes and piping systems, condensers, ocean thermal energy conversion (OTEC) plants and offshore oil rigs, sonar domes, navigational buoys, moored oceanographic instruments, and fishing gear. Biofouling in freshwater systems is less pronounced as compared to sea-water systems and generally manifests in the form of condenser slime in power-plant cooling circuits. Occasionally, clams and aquatic vegetation also cause fouling problems in plants using river water. In spite of great advances over the years, biofouling control is still a formidable problem in cooling circuits of power plants, ship hulls, oil platforms and other marine structures. While the advent of antifouling paints provided some relief initially for protection against biofouling on ship hulls and other marine structural materials, recent concerns on the toxicity of many of the newer formulations like tributyl tin has precluded their large-scale application. With regard to condenser-cooling systems of power plants, chlorination has been the method of choice for fouling control over the years. However, fears regarding the carcinogenicity of chloroorganics has led to a search for newer biocides like ozone and for novel chlorination practices like targeted chlorination to reduce chlorine residuals in the discharges.

1.1. *Fouling on ship hulls*

Biofouling can be defined as massive growth and development of marine life on materials in contact with the marine environment. Historically it is reported that British admiralty thought of abandoning its iron ships due to the biofouling problem. Barnacles are the most common fouling organisms encountered on ship hulls although other foulants like oysters, mussels, ascidians, bryozoans and polychaetes also contribute substantially to the total biomass. According to Christie and Dalley,[3] changes in shipping operations over the years have led to changes in the type of barnacles that foul the ships. With the use of noncopper-based alloys and other materials for ship hulls, accelerated attachment of microfouling organisms and the subsequent development of macrofouling community has become very common. Application of modern antifouling paints coupled with dry docking and cleaning have been the most effective approach in controlling the problem of fouling on ship hulls. Some of the well-known effects of ship hull fouling include significant loss of maximum speed as well as range, accelerated hull corrosion and decreased maneuverability.

1.2. *Fouling on offshore structures and fouling-prevention technologies*

Offshore oil platforms are designed for a life span of 20–30 years, and often fouling of these structures is of great concern.[4] Excessive biofouling increases their sectional area, alters the surface roughness and consequently increase hydrodynamic loading.[5, 6] Coatings, claddings, and cathodic protection systems are usually employed to protect offshore structures. However, antifouling paints, which have usually a life span of 2–3 years and are used to protect ship hulls, are of little practical value in protecting offshore structures as they are submerged in sea water all the time. About 8% of the lifetime cost of a platform is expended on antifouling measures. Haderlie[7] reported that loading induced by waves is concentrated in the upper 30 m of the structure below the mean water level. In the North Sea where fouling of offshore structures is quite severe, maximum fouling is in the upper 30 m and maintenance cleaning to relieve loading is confined to this depth.[8] Fouling in the offshore Arabian Sea, similarly, is heavy only in the upper 22 m where biomass build-up is about 10 $kg/m^2/y$, whereas at 42 m, biomass values were only 1/10 of that at 22m.[9]

Divers using high-pressure water jets usually do mechanical cleaning of platform legs. The kinetic energy of the water that leaves the nozzle determines the rate at which work (i.e. removal of fouling) is done.[10] The kinetic energy is related to the velocity of water, which in turn is proportional to the pressure.[11] The shock wave energy generated by a water jet of 20,000 psi exceeds the strength of even the most adherent fouling build-up.

A few preventive measures are also used, including antifouling claddings. These claddings can be of inherently antifouling materials such as 90/10 cupronickel or elastomers. While cupronickel offers protection, serious galvanic corrosion can result if proper insulation is not provided between the cladding and the platform jackets. Elastomers, on the other hand, contain toxicants and can be made to a thickness of 10 mm or more. They, therefore, are longer lasting than ordinary antifouling paints[12] and provide significant long-term protection.

1.3. *Fouling in sea-water cooling systems of power plants*

Steam-power-generating stations are increasingly being located in the coastal areas because of the easy availability of unlimited cooling water for the condensing phase of steam turbine operation. In sea-water cooling systems, biofouling by marine invertebrates is generally a problem of considerable interest in the context of ensuring smooth and efficient operation of the power plant. The species which cause fouling problems in the cooling-water systems vary from plant to plant. On an average, a nuclear power plant with an installed capacity of 235 MW (e) (twin units) like the Madras Atomic Power Station (MAPS), Kalpakkam, requires approximately 35 m^3/s of water for turbine condenser-cooling purposes and process water cooling.[13] Many sessile organisms appear to live happily in the cooling-water circuits of these plants. The conditions which favour the attachment and development of these organisms in power-plant cooling circuits are the continuous flow of sea water supplying oxygen and food, reduced silt deposition, the lack of competition from algae in the culverts and a reduction in the density of predatory organisms. Severe operational problems have occurred in such plants such as fouling-induced flow resistance in cooling-water circuits leading to significant pressure drops in the system. Accumulation of mussels and barnacles often impedes the flow of cooling water flow rates and reduces pump submergence in these plants.

1.3.1. *Problems due to macrofouling in the cooling-water conduits of MAPS*

The intake sub-sea bed tunnel of MAPS was constructed during the period 1974–76 and has since been flooded with sea water (Fig. 1). Chlorination on an intermittent basis (for 1 h once in an 8-h shift) at the rate of about 1 to 2 ppm residual has been used as a biofouling-control measure in the tunnel since 1979. The MAPS Unit I was commissioned in July 1983 and Unit II in September 1985. During the start-up of Unit II pumps in March 1985, large quantities of green mussel shells appeared on the travelling water screens in the forebay. This was quite contrary to expectations as it was firmly believed that biofouling in the system has been effectively prevented by chlorination which has been in force since 1979. Subsequent to this observation, several investigations were directed to understand the problem of biofouling in Kalpakkam coastal waters.[14–18]

During the annual shutdown for maintenance of MAPS Unit I in October 1984, it was observed that several condenser tubes were blocked by green mussel shells. This was followed by an incident during which mussel shells weighing about 50 tonnes got collected on the travelling water screens in March 1985 when Unit II circulating water pumps were started prior to commissioning the unit. Although these observations were symptoms of biofouling in the pre-condenser sections of the sea-water cooling system, they did not constitute any immediate problem for the plant. Subsequently, in 1986 when both units were in full power operation, it was observed that water levels in forebay were going down significantly below design limit. This has adversely affected the operation of sea-water pumps by way of increased vibration and cavitation, often leading to breakdown. It was not very clear at that stage as to whether biofouling was responsible for the observed pressure drop in the forebay or some other blockage had caused this hindrance. To clear doubts in this regard, plant authorities decided to arrange physical inspection of the tunnel with the help of diving personnel. Thus, a diving inspection was organized in December 1987. The diving was preceded by the inspection of the

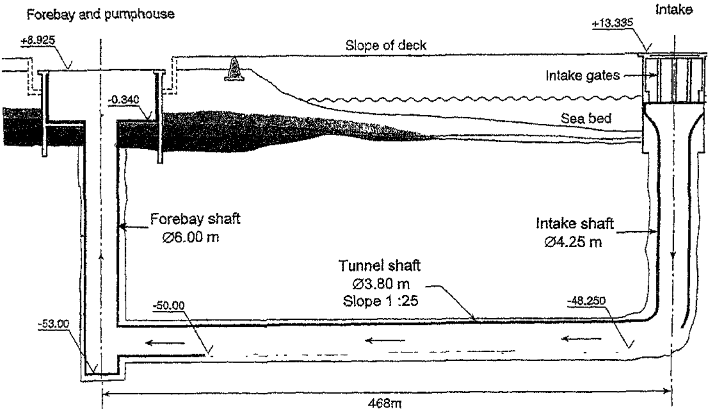

FIG. 1. A schematic diagram of the Madras Atomic Power Station (MAPS) sea-water intake tunnel at Kalpakkam

tunnel by a remotely operated vehicle mounted with a video camera. The diving inspection and the video pictures revealed extensive fouling by green mussels. A list of fouling organisms observed during the inspection and the quantitative abundance of the dominant species are given in Tables I and II, respectively.

1.3.2. *Fouling control in the tunnel*

Although extensive fouling by green mussel was observed in the sub-sea bed tunnel, there was no way of cleaning up the system to restore forebay water levels. Global enquiries have shown that there is no available technology to clean up the system. Thus, on experimental basis, shock chlorination at about 2.0 ppm residual was resorted to for about a week to kill the well-established adult mussel community in the tunnel system. While no immediate effect was seen, after about a fortnight, mussel shells started appearing on the travelling screen in the pump house in large quantities and about 60% of the resident population was removed by this procedure. Once this amount of cleaning was done, pressure drop situation eased and forebay water levels showed significant improvement. Ever since this incident, continuous low-dose chlorination at a residual of 0.5 ppm (exomotive chlorination) is being practiced in the station to prevent the mussel spat from settling within the tunnel system. Subsequent studies have shown that this chlorination regime is effective in checking new settlement of mussels in the tunnel system.

1.3.3. *Qualitative and quantitative assessment of fouling at MAPS*

Artificial substrates like panels made of teak wood, asbestos, glass, perspex, etc. were used to study the settlement of fouling organisms over the period 1985 to 1990 at Kalpakkam.[16, 19]

Table I

List of fouling organisms observed in the cooling-water system of the Madras Atomic Power station (MAPS)

Phylum: Porifera
- **Sponges**
  - *Callyspongia diffusa* (Ridley)
  - *Mycale mytilorum* (Annandale)
  - *Tendania anhelans* (Lieberkuhn)

Phylum: Coelenterata
- **Hydroids**
  - *Obelia bicuspidata*
  - *Sertularia* sp.
- **Sea anemones**
  - *Sagartia* sp.
- **Gorgonium**
  - *Gorgonia (Leptogornia) minacea (*Esper*)*
  - *Echinogornia* sp.

Phylum: Ectoprocta
- **Bryozoans**
  - *Electra* sp.
  - *Acanthodesia* sp.
  - *Bugula* sp.

Phylum: Annelida
- **Tube worms**
  - *Serpula vermicularis* (Linnaeus)
  - *Hydroides elegans* (Zibrowias)
  - *Mercierella enigmatica* (Fauvel)

Phylum: Arthropoda
- **Barnacles**
  - *Balanus amphitrite* (Darwin)
  - *Balanus amaryllus* var *euamaryllis* (Broch)
  - *Balanus reticulatus* (Darwin)
  - *Megabalanus tintinnabulum* (Linnaeus)

Phylum: Mollusca
- **Green mussels**
  - *Perna viridis* (Linnaeus)
- **Brown mussels**
  - *Perna indica* (Kuriakose & Nair)
- **Oysters**
  - *Crassostrea madrasensis* (Preston)
  - *Pinctada anomioides* (Recre)
  - *Chama reflexa* (Philippi)
  - *Saccostrea cucullata* (Born)
- **Modiolus spp.**
  - *Modiolus modiolus* (Linnaeus)
  - *Modiolus undulatus* (Dunker)
  - *Modiolus striatulus* (Hanley)
  - *Modiolus philippinarum* (Hanley)
- **Clams**
  - *Beguina variegata* (Bruguiere)
  - *Arca arellana* (Lamarck)
  - *Irus exoticus* (Hanley)
  - *Timoclea arakana* (G&H Nevill)
  - *Paphia textile* (Gmelin)
  - *Donax cuneatus* (Linneaus)
- **Snails**
  - *Euchelus asper* (Gmelin)
  - *Thais rugosa* (Born)
  - *Thais blanforti* (Melvill)
  - *Thais tissoti* (Petit)
  - *Gyrineum natator* (Roeding)
  - *Cypraea gracilis* Gaskoin
  - *Cymatium pilaire* (Linnaeus)

Phylum: Echinodermata

Brittle stars
- *Amphioplus graveylii* James
- *Ophiothrix exigua* Lyman

Phylum: Chordata
- **Subphylum: Urochordata**
- **Ascidians**
  - *Didemnum psammathodes* (Sluiter)
  - *Lissoclinum fragile* (Van Name)
  - *Symplegma brakenhielmi* (Michaelson)
  - *Diplosoma macdonaldi* (Herdman)

Seasonal distribution of major fouling organisms observed at Kalpakkam showed barnacles to be settling on the panels throughout the year. Hydroids were another important group of foulants. They settled continuously on test panels also with peaks during April, October and February. In general, it is reasonable to conclude that in Kalpakkam water-fouling community reaches a stable point dominated by either green mussels or ascidians. It was found that if mussel spat are abundant during any given year, mussels are found to dominate the panels and fouling community is invariably dominated by them. In the event of mussel spat being absent, ascidians would be the dominant member of the fouling community. However, fouling community succession was quite different at forebay and outfall. Ascidians were totally absent at both these sites. Macrophyte *Enteromorpha* was found to be a major foulant at the outfall. Similarly polychaetes dominated the forebay panels. Both locations showed low species diver-

Table II
Total fouling biomass (tonnes) in the entire MAPS submarine tunnel system

Fouling organism	Intake shaft	Tunnel	Forebay shaft	Total biomass
Perna viridis	50.89	253.16	107.25	411.30
P. indica	0.00	54.11	3.82	57.93
Crassostrea madrasensis	0.22	2.76	0.71	3.69
Arca arellana	0.00	0.00	2.55	2.55
Beguina variegata	0.00	0.00	2.77	2.77
Modiolus spp.	1.54	9.86	1.76	13.16
Thais bufo	0.24	9.91	0.98	11.13
T. tissoti	0.07	3.25	0.48	3.80
Euchelus asper	0.06	1.92	0.43	2.41
Megabalanus tintinnabulum	1.37	32.02	1.33	34.72
Miscellaneous*	6.57	19.51	8.49	34.57
	60.96	386.50	130.57	578.03

*This includes those species whose contributions to the total biomass individually were less than 2 tonnes

sity, relatively low biomass levels and growth rates of fouling organisms, possibly due to the altered environmental conditions like elevated temperature and presence of chlorine residuals at these locations.

2. Fouling problems in OTEC plants

Pioneering work on biofouling and corrosion of materials used in OTEC systems was carried out by Argonne National Laboratory (ANL), USA, through a biofouling, corrosion, and materials (BCM) project which was established at ANL in March 1978. Due to the low temperature difference between sea water and the working fluid, usually ammonia in OTEC heat exchangers, a large heat-transfer coefficient must be maintained to realize significant net power from an OTEC plant. Cleanliness of heat exchanger plates is therefore a critical operational requirement of the OTEC concept. Experiments carried out at the BCM project were with shell and tube-type heat exchangers with materials like aluminum 5052, titanium SB-337, stainless-steel Al-6X and copper-nickel alloy 90–10. Fouling resistance calculated for these materials showed titanium exhibiting the characteristic 'conditioning period' with little change in the fouling resistance during the first four weeks. Aluminum and stainless steel were fouled at the expected rate, whereas cupro-nickel supported very little biological activity through the first two weeks. The three methods which were recommended by the BCM project were the use of flow-driven brushes, recirculating sponge balls and chlorination to ensure condenser cleanliness.

3. Biofouling in freshwater cooling systems

In freshwater-cooling systems, whether it is a cooling tower, cooling pond or a once-through cooling system, biofouling is essentially due to the growth of bacteria and protozoa and sometimes fungi in the condenser tubes as well as due to the growth of algae and fungi in the cooling towers. Although there have been instances of flow blockages by freshwater clams of *Cor-*

bicula sp. (Asiatic clam) in nuclear power stations in USA, there are no reports of such occurrence from power stations in India.

Biofouling control in freshwater circuits is generally achieved by intermittent chlorination. The generally accepted chlorination schedule is two to three cycles per day each lasting 30 to 60 minutes. The frequency of the cycles is determined after assessment of the rate of slime build-up during the off-periods of chlorination. Generally effective biofouling control in freshwater circuits is possible if data on seasonal variation in chlorine demand and the rate of slime build-up are available. Most slime-forming bacteria get killed at a residual chlorine level of 0.5 ppm for 10 minutes and even some of the more resistant groups like iron and sulfur bacteria are killed at 1.0 ppm for one hour. In cooling towers, the upper limit of chlorination is generally fixed at 1.0 ppm to prevent wood deterioration. At such chlorine levels, a contact time of two hours would be necessary to control algal growth in the tower structure.

4. Economic losses due to fouling problems

Estimates of economic losses due to biofouling are often very large. Losses as a result of shutdown of a 235-MW(e) power station due to biofouling were estimated to be about Rs. 40 lakhs a day[20] (about $100,000). According to Chow *et al.*,[21] the increase in condenser backpressure due to fouling in a 250-MW (e) plant costs about $250,000 annually. Fouling by Asiatic clam *Corbicula asiatica* in condenser tubes of power plants alone costed the United States over $1 bn annually.[22] In 1975, the US Navy spent over $15 mn annually on material and labour used in applying antifouling coatings. As per Haderlie[7], the U.S. Navy has spent about $150 mn for additional fuel used to overcome the drag created by fouling on ship hulls. Fouling of 15-cm thickness on an offshore platform was reported to cause an estimated 46% wave loading. Mechanical cleaning of such fouling by the use of high-pressure water jets can cost as much as $100,000 annually. Studies by Coughlan and Whitehouse[23] showed that between 1957 and 1964, 4,000 condenser tubes failed due to mussel fouling leading to leakage of cooling water into the boiler. Apart from the loss of power generation, these leaks contaminated the feed-water system and accelerated the boiler waterside corrosion, resulting in boiler tube failures. This has necessitated the inlet culverts to be drained for manual cleaning at least once a year. Average quantity of mussels removed was estimated at 40 t/y and the maximum was as high as 130 t/y. Similar observations were recorded at the Pools Power Station (Dorset) where 300 tons of mussel shells were removed a year.[23] About 300 tons of mussels were removed following shock chlorination treatment from Madras Atomic Power Station intake tunnel on one occasion.[24] Rippon[25] showed that investigations by the CEGB team on biofouling control practices showed that stress corrosion cracking of admiralty brass condenser tubes could be attributed to ammonia produced by bacteria.

The cleaning of fouling from the cooling-water circuits of power plants is generally very expensive, for example, 4000 man-hours were used to clean the circuits and to remove 360 cubic meters of mussels at Dunkerque in 1971.[26] Another example was the intense fouling problems of the Carmarthen Bay Power Station which was commissioned in 1953. Within a year the problem became so severe that the plant was shut down daily and regular operation of the plant was almost impossible.[27] The underwater cooling conduits of the Tanagwa power station in Japan showed fouling thickness of 70 cm. A large quantity of jellyfish (150 t/day) was also removed from this station in one instance.[28]

The Kansai Electric Power Corporation, Japan, showed a high rate (94%) of condenser tube failures. Analysis revealed that tube failures were related to macrofouling lodged in the tubes.[28] The development of condenser backpressure due to fouling of cooling-water circuits is a common problem which in a 250-MW(e) plant can cost the utility about $250,000 annually.[21] A 5-mm Hg reduction in condenser backpressure is equal to 0.5% improvement in turbine heat rate which is approximately equal to 3 additional megawatts of generating capacity.[29] It has been reported that up to 3.8% loss in unit availability in large power plants could be attributed to poor condenser tube and auxiliary system reliability.[30] A 250-micron-thick layer of slime may result in up to a 50% reduction in heat transfer by a heat exchanger.[31]

5. Fouling control practices

Fouling control measures used by various industries depends on the type of industry and the type of substratum. For example, in the case of ship hulls, toxic antifouling paints have been the mainstay, while in the case of offshore oil platforms mechanical cleaning by hydrojets has been the method of choice. Control measures adapted with advantage in one situation or in one biotic environment may not be equally effective in other situations. The establishment of a fouling community can be divided into different phases. Initially, a primary film develops which comprises bacteria, fungal spores, diatoms and colloidal organic matter. This is followed by a second phase, which comprises the settlement and metamorphosis of larvae of macrofouling organisms. The development of a suitable control measure is dependent on the type of fouling organisms present at the particular site and the flexibility in the system designs to adapt preventive strategies. Selection of control measures is governed by many factors: efficacy, cost, and environmental acceptability. Although physical methods like the construction of barriers (screens) to prevent the entry of fouling organisms and provision of increased flow velocities, heat treatment and mechanical cleaning offer some temporary relief, they do not offer permanent remedy to all fouling problems in cooling conduits. Chemical methods have been more successful in preventing the settlement of organisms to a greater extent. Some of the chemical methods currently in practice are discussed in the following section.

5.1. *Antifouling paint technology*

In the past, the alternative to mechanical cleaning of surfaces has been to use either a) coating based on copper and copper alloy systems, b) coatings containing active biocides (contact leaching and soluble matrix type), or c) coatings with low-energy surfaces. A typical antifoulant paint has three components, a binder (a polymeric compound to hold the paint together), a resin (a water-soluble compound to allow sea-water access to the toxin) and a toxin (to confer antifouling property to the paint). The primary disadvantage of antifouling coatings is that they wear out and must be replaced periodically. Coatings of the contact-leaching type have an insoluble matrix (which is left intact) containing copper thiocyanate, copper powder or cuprous oxide as the principal biocide at the coating surface. Subsequently developed contact-leaching antifouling paints contained organometallic compounds such as copper oxide, tri-butyl tin oxide (TBTO) or tributyl tin flouride (TBTF), triphenyl lead acetate (TPLA) or triphenyltin fluoride (TPTF) which was found to be more effective. In the contact-leaching type of paints the toxic material is continuously leached from the coating surface. On the contrary, in soluble matrix paints the active material is incorporated into a resin binder which slowly and continuously dissolves releasing both the biocide and the matrix from the surface. In both the cases, the lifetime of the paints is between two and five years.[32] However, the discovery of new binder systems such as vinyl-chlorinated rubber and epoxy resins has led to the development of physically tougher systems. A further development in antifouling technology is the self-polishing polymer composed of polymers into which organotin acrylates are incorporated. In this case, the biocide is incorporated into the polymer which hydrolyses continuously and both the biocide and polymer are released together.

Environmental concerns about the use of toxic antifoulants have led to increased interest in the development of nontoxic alternatives.[33] Recent legislation banning the use of organotin-based paints[34] and metallic compounds in antifouling formulations has resulted in the search for an environmentally safe, biologically active substance showing antifouling properties against the target organism.

5.2. *Nontoxic foul-release coatings*

One of the emerging technologies is the nontoxic foul-release coating. In contrast to conventional antifouling coatings these have no inherent antifoulant properties. Foul-release coatings generally rely on the principle that adhesion of organisms to surface is weak when surface-free energy of the solid is low. This is because, in the process of adhesion, the work required to separate a liquid, e.g. a bioadhesive cement, from a solid, is equal to the sum of the surface-free energy of the surface and the surface tension of the liquid, minus the interfacial surface tension between the solid and the liquid.[35] Hence, the lower the surface-free energy, the weaker the adhesion. If the surface-free energy of the solid is less than the surface tension of the liquid, then the liquid will not strongly adhere to the solid. This can be seen from the fact that surfaces of lower energy will produce a large contact angle with a liquid (the angle formed between the plane of the solid surface and a straight line that is tangent to a drop of the liquid at the point of contact between the two) than a surface of higher energy.

To adhere to surfaces, fouling organisms synthesize and secrete proteinaceous adhesives that provide secure attachments between the organisms and the surfaces. Materials with low surface-free energy, as explained above, offer low adhesion strength, resulting in poor attachment. Research indicates that the low surface-free energy approach to antifouling is feasible and practical types of materials used are fluorinated polyurethane and silicone-based coatings. Silicon elastomers, which are more recent than fluoropolymers, are more efficient.

There are also other nontoxic materials such as epoxy-based coatings, elastomeric urethanes, and hydrophilic copolymers. Silicone-based coatings performed best with a service life of two to four years. These coatings did foul, but growth could be easily removed by fast-flowing water. Moreover, because massive build-up of fouling is prevented, the problem is made more manageable. In 1989, the average installed cost of this treatment was \$5–10 per square foot, depending on local labor costs and other site-specific factors.

5.3. *Mechanical methods*

Both manual and mechanical methods such as scraping, Taprogge and Amertap systems (American MAN system)[28, 36, 37] have been used to keep the condenser tubes clean. Manual methods include periodic cleaning with rubber plugs, nylon brushes or metal scrappers. This method can improve the heat-transfer efficiency where the condenser cooling water is fairly clean. However, this method is becoming uneconomical particularly in large-size condensers owing to long shutdown times for cleaning. The Amertap system which employs sponge rubber balls has been in vogue in most of the power stations in Europe.[29] However, these mechanical devices are of little use in plate or fin-type heat exchangers.

5.4. *Flow*

The type and amount of substrate fouling is dependent on the relative motion between sea water and the substrates. Thus, increased flow velocities can be used effectively as a control strategy to prevent/reduce settlement of fouling organisms. At high flow rates the shear stress of the water often exceeds the shear strength of many organisms. Experience at Vado Ligure Power Station indicates that a precondenser culvert of 1400–1500-m length has been kept fouling free by maintaining a velocity of 11 m/s.[26]

5.5. *Heat treatment*

This method of fouling control has been used by Southern California Edison Company on the California coast in USA, La Spezia in Italy, the Eem's plant in Netherlands and in Russia. Here the heated effluents from the condenser diverted through the intake tunnel which when passed through the condenser a second time picks up more heat. The frequency of heat treatment is decided by the rate of recolonisation of fouling. It has been estimated that a residence time of one hour at 40°C is enough to eliminate mussel and other fouling organisms. Some of the disadvantages of this treatment are that (a) this cannot be tried in an existing power station wherein the system is not designed for heat treatment, (b) the power station has to operate at reduced power levels during the period of treatment and (c) it cannot control slime in the condensers.

5.6. *Chemical biocides*

5.6.1. *Oxidizing biocides*

Several oxidizing biocides like chlorine, bromine, bromine-chloride, chlorine dioxide and ozone have been used for treatment of cooling water. Each one of these has its own merits and demerits.

5.6.1.1. *Chlorine*

Although alternative chemical biocides are available, chlorine still remains the most common method of biofouling control in cooling water systems[38, 39] because of its effectiveness, easy availability and relatively low cost. It is effective in removing both slime in condensers and macrofouling in the precondenser sections. The biocidal action of chlorine is due to its oxidizing capacity.

The deleterious effects of chlorine on bacterial cells are many. Some of these are *in-vitro* formation of chlorinated derivatives of purine and pyrimidine nucleotides, oxidative decarboxylation of amino acids, inhibition of enzymes involved in intermediary metabolism, inhibition of protein synthesis, introduction of single- and double-strand lesions in the bacterial genome, inhibition of membrane-mediated active transport processes, respiratory activity, and oxidative phosphorylation.

Chlorination practices are greatly influenced by hydrographical conditions of the site, physical location of intake system, nature of fouling community and the quality of sea water. The optimum chlorination for a system depends on the maximum utilization of chlorine dosed into the cooling water system for preventing the growth of foulants, maintaining a minimum level of residual chlorine in the cooling water system and the rapid decay of chlorine at the outfall.

Due to safety problems associated with transport and storage of chlorine, attempts have been made for alternative forms of chlorine. Liquid hypochlorite solution and chlorine from electrolysis of brine or sea water have been tried in the United Kingdom. The safety problems associated with transport and storage are eliminated with the use of electrochlorination. However, the production cost is 20% higher than liquid chlorine and other safety problems associated with the production of hydrogen gas and poor efficiency of the electrolysis process at lower temperature are some of the drawbacks of electrochlorination. One of the major concerns in the context of chlorine whatever the form in which it is applied is its long-term potential threat to marine life, and carcinogenecity of chloroorganics produced during chlorination.

Because of the above-mentioned problems, the United States Environmental Protection Agency (EPA) has issued guidelines restricting the daily chlorine discharges (as total residual oxidant) from power plants to be no more than 0.2 ppm for two hours.[40] Such restrictions on the use of chlorine have forced many industrial units to look for alternative biocides or for alternative chlorination practices like targeted chlorination.

Targeted chlorination (TC): This is a novel technique for feeding chlorine to control fouling of condenser tubes, while allowing power-plant operators to meet the new EPA effluent limitation for chloramine discharges. Most power plants inject chlorine into the condenser cooling water system at the intake pump suction. The chlorinated water is made to flow several hundred meters to the condenser and back to the environment. Many industries find the EPA limit too low to maintain the condenser efficiency. The concept of TC as outlined by Moss *et al.*[41] is to sequentially chlorinate a few condenser tubes at a time using relatively high chlorine concentrations to destroy the microorganisms present in the tubes. In this method, the total chlorine consumption could be reduced by 70%. Some of the common designs where TC was found to be more promising were (1) fixed nozzles in the inlet water box, sequentially fired to chlorinate small groups of tube at a time and (2) a movable manifold located against the tubesheet, which would target a selected section of tubes.

5.6.1.2. *Bromine*

Bromine in different forms can be a simple, cost-effective alternative to chlorination for biofouling control.[42] Although bromine is delivered in different practical forms such as bromochlorodimethyl hidantion, activated bromide and bromine chloride, it is the hypobromous acid (HOBr) formed during hydrolysis which is responsible for its biocidal action. Bromine is attractive because of several advantages: (1) rapid residual decay due to low vapor pressure (one third of chlorine), (2) superior disinfection properties due to rapid oxidation, (3) high solubility, (4) relatively high density permitting 3,000 lb of liquid bromine to be supplied in a container, (5) viability in a broader range of concentrations, (6) HOBr is a weak acid, 7) more economical and 8) reduction in exposure time due to superior biocidal efficiency. Moreover, bromamines are more active and faster acting than the corresponding chloramines making HOBr more effective than HOCl in ammoniacal environments.

5.6.1.3. *Chlorine dioxide*

Chlorine dioxide offers some unique advantages due to its selectivity and effectiveness over a wide pH range. It is a very strong oxidant, highly soluble (20,000 ml/l at 4°C) and unstable leaving hardly any residuals. Unlike chlorine, chlorine dioxide remains a true gas dissolved in solution. The lack of any significant reaction of chlorine dioxide with water is partly responsible for retaining its biocidal effectiveness over a wide pH range. This property makes it a logical choice for cooling systems operated in the alkaline pH range or cooling systems with poor pH control. Chlorine dioxide added to a system is available as a biocidal agent and is not consumed to the degree that chlorine would be under the same circumstances. Chlorine dioxide reacts very slowly with secondary amines and not with primary amines and ammonia as in the case of chlorine. Some concerns are with regard to its safety and storage. As chlorine dioxide is a gas it is highly unstable and must be generated on site.

5.6.1.4. *Ozone*

Ozone is well known for its bactericidal properties.[43] It is a stronger oxidant and is very effective due to its high oxidation potential. It is also less toxic and less persistent than chlorine. Its potential for biofouling control has been tried at the Public Services Electric and Gas Company Plant, New Jersey, USA. Some of its disadvantages are the difficulty to achieve uniform distribution, high ozone demand in the presence of bromide, large space required by the ozonizer, necessity for on-site generation and high costs.

5.6.2. *Nonoxidizing biocides*

With the environmental regulations imposed by EPA on the use and application of oxidizing biocides such as chlorine and bromine, research has been underway for alternative biocides by commercial bodies. 'Clamtrol' (Betz Dearborn) is an example of a nonoxidizing biocide currently in use in the Asian and European countries. Several other chemicals such as Acrolein (highly toxic and highly flammable), 1,2-benzisothiocyanate, tannic acid, acrylamides and quarternary ammonium compounds have been used and were found to be effective in repulsing macrofouling.[36]

6. Conclusion

Biofouling and its prevention continues to pose serious challenges to many maritime operations including shipping, offshore structures, OTEC plants and sea-water intake systems of power plants and other industries which use sea water for cooling purposes. On ship hulls foul-release coatings are now being widely adapted with advantage. Offshore structures still use mechanical cleaning systems like high-pressure water jets. In sea-water cooling circuits of power plants, chlorination is still widely used, although progressively *in situ* electrochlorination is being adopted in new power stations. Experimentally it has also been shown that *in-situ* electrochlorination can be used to protect underwater sensors of marine instrumentation. In OTEC plants, chlorination in combination with mechanical cleaning has been used to achieve condenser cleanliness in shell- and tube-type heat exchangers. However, with the present tendency to increasingly use plate-type heat exchangers, newer strategies have to be developed to achieve maximum heat-transfer efficiency.

A comprehensive plant inspection and monitoring program should be mandatory to increase the reliability of the cooling water system. A design evaluation to determine the components most likely to become fouled and the areas where increased monitoring and maintenance are required should be mandatory for all plants. The spawning seasons and growth rate characteristics of the fouling organisms must be studied to adapt a suitable control regime. The overall heat-transfer coefficient of heat exchangers should be monitored as a part of the surveillance procedure to assess the performance. Side-stream fouling monitors should be used in suspect locations. Exposure panels should be used to monitor the settlement and growth of fouling organisms in the cooling water source.

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