Biofouling and its control in seawater cooled power plant cooling water system - a review

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1. Introduction

Biofouling may be defined as the attachment and subsequent growth of a community of usually visible plants and animals on manmade structures exposed to seawater environment. Man has long been aware of this problem. In the fourth century B.C., Aristotle is reported to have stated that small "fish" (barnacles) were able to slow down ships. Fouling of ship hulls, navigational buoys, underwater equipment, seawater piping systems, industrial or municipal intakes, beach well structures, oil rigs and allied structures has often been reported. In the past few decades, the list of affected structures has expanded. Now, reports are common regarding the biofouling that affects Ocean Thermal Energy Conversion (OTEC) plants, offshore platforms, moored oceanographic instruments and nuclear and other submarines. The impact of biofouling on sea front structures is staggering. Ships show a 10% higher fuel consumption caused by increased drag and frictional resistance resulting from hull and propeller fouling. Water lines lose their carrying capacity and speed of flow owing to biofouling growth along pipe systems. The heat exchanger performance declines due to attachment of biofoulants. Many marine organisms themselves face the constant problem of being colonized and overgrown by fouling organisms. Immobile plants and animals are generally exposed to biofouling and consequent loss of species and community assemblages. Biofouling also promotes corrosion of materials. The money and material needed for fouling protection measures are indeed exorbitant. It is estimated that the marine industry incurs an expenditure of 10 billion sterling pounds a year to combat the situations arising from biofouling worldwide (Satpathy, 1990). A lot of research effort has been devoted to understand the fundamental ecology and biology of fouling environments, organisms and communities in diverse settings.

The huge requirement of cooling water as well as accrescent demand on the freshwater has led to the natural choice for locating power plants in the coastal sites where water is available in copious amount at relatively cheap rate. For example, a 500 MW (e) nuclear power plant uses about 30 m^3sec^{-1} of cooling water for extracting heat from the condenser and other auxiliary heat exchanger systems for efficient operation of the plant. However, use of seawater, brings associated problems such as colonization of biota which stands in the way of smooth operation of the plant. Unfortunately, every cooling system with its concrete walls forms a suitable substrate for marine growth. Some of the conditions which favour the development of a fouling community in power plants are (a) continuous flow of seawater rich in oxygen & food, (b) reduction in silt deposition, (c) lack of competition from other communities and (d) reduction in the density of predators. Broadly speaking the effects of marine growth on the power plant are (a) losses in plant efficiency, (b) mechanical damage and (c) problem for the integrity of the cooling circuits needed for safety of nuclear plants (Nair, 1987). Hence biofouling control aims to achieve efficient operation of the power station at all times. It is therefore necessary for power plant designers to make a rational choice regarding the most suitable control method to combat biofouling problem in a practical, yet economically feasible & environmentally acceptable manner.

1.1 Economic impacts of biofouling

Economics involved in the biofouling problem of power plant as quoted by various authors are cited here to emphasize the importance of biofouling control.

A 5mm Hg condenser back pressure improvement can equal to 0.5% improvement in the turbine heat rate which approximately equal to 3 additional megawatts of generating capacity (Drake, 1977). Similar increase in condenser back pressure due to fouling in a 250 MW (e) plant can cost the utility about $ 2.5 lakhs annually (Chow et al., 1987). One report estimates that fouling by Asiatic clam alone costs the nation over a billion $ annually (Strauss, 1989). Costs for one day unplanned outage can run into 0.3% of their earning per year, taking 300 days operation. Hence eliminating one unplanned outage can more than pay for measures taken to maintain cooling water tube cleanliness. Waterside resistance accounts for 72% of the total resistance to heat transfer of the tube. Of this, the film which forms in a condenser tube accounts for a significant 39% and the rest 33% is due to scaling (Drake, 1977).

The experience of Marchwood (Southampton) showed that between 1957 and 1964, 4000 condenser tubes failed due to mussel fouling leading to leakage. Apart from the loss of generation, these leaks contaminated the feed water system and accelerated the boiler water side corrosion, resulting in boiler tube failures (Coughlan and Whitehouse, 1977). The inlet culverts had to be drained for manual cleaning at least once in a year. Average quantity of mussel removed was 40 tons but could be as high as 130 tons. Similar stations at Pools (Dorset) had a maximum 300 tons (Coughlan and Whitehouse, 1977). About 300 tons of mussel shells were removed each time by shock chlorination from MAPS intake tunnel on two occasions. Cost (at 1975 prices) of dropping a 500 MW (e) oil-fired station at Fawley (Southampton) was 15000 pounds per day due to fouling, excluding repairs. The cost of chlorine for this unit for the whole year of 1975 was 7500 pound. The consequence of inadequate chlorination at Inland station eventually led to the unit being taken off load for manual cleaning of condenser (Coughlan and Whitehouse, 1977). It has been observed by the CEGB investigating team on biofouling control practices that stress corrosion cracking of admirality brass condenser tubes was attributed to ammonia produced by bacteria (Rippon, 1979).

The cleaning out of biofouling from the cooling water intake tunnels and culverts is generally very expensive; for instance 4000 man hours were used to clean the culverts and to remove 360 m^3 of mussels at Dunkerque in 1971 (Whitehouse et al., 1985). Within a very short time at Carmarthen Bay Power Station, which was commissioned in July 1953, seed

mussels and various species of marine life were noticed around the main intake to the cooling water system. By april 1954 the fouling was so severe that plant was shutdown daily, increasing to 3 times per shift by mid July when operation of the station became almost impossible (James, 1967). At the Tanagwa Power Station in Japan the concrete under ground conduit was covered with layers of attached organisms sometimes measuring to about 70 cm thickness. A large quantity of jelly fish (150 tons/day) was also removed from this station in one instance (Kawabe et al., 1986).
An analysis of all tube failures at Kansai Electric Power Corporation (Japan) in 1982 and 1983 showed that 94% of all tube failures were related to macrofouling lodged in the tubes (Kawabe et al., 1986). Microfouling seems to be a major obstacle to the successful development of the ocean thermal conversion concept into a useful solution to the world's energy supply (Corpe, 1984 and Darby, 1984). 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 (Syrett and Coit, 1983). A 250 micron thick layer of slime may result in up to a 50% reduction in heat transfer by heat exchangers (Goodman, 1987).

1.2 Bio-growth in different sections of a cooling water system

A typical cooling water system of a power plant involves a pre-condenser system and the heat exchangers which includes main condenser and process water heat exchangers. The pre-condenser system involves the intake structures and the cooling water system from intake to the pump house. The intake system is either an open canal or pipeline or a tunnel. It has been observed that macrofouling generally takes place in the pre-condenser system whereas, microfouling is observed in the condenser and process water heat exchangers. This could be due to difference in the various features like flow, temperature, space etc at different parts of the cooling water system. In spite of various physical measures such as trash rack, intake screen, travelling water screen, to control biofouling, the tiny larval forms of various organisms enter the system, settle and colonize inside it and finally affect the smooth operation of the cooling water system. These organisms clog cooling water flow endangering the safety-related systems at some power plants. During the construction, when the tunnel is ready and the biocide treatment plant is yet to be operational, the intake structure gets severely fouled by macrofoulers. Despite efforts to provide an effective design of heat exchanger and careful attention to the maintenance of the design operating conditions, it is likely that fouling on the water side of the heat exchangers will occur unless suitable precautions are taken. The common practice of taking water from natural sources such as rivers and lakes for cooling purposes means that it contains micro- and macro-organisms, which will colonize the heat transfer surfaces, to the detriment of cooling efficiency. The problem will be aggravated by the fact that the temperature of the waterside surface in the heat exchanger is usually close to the optimum temperature for maximum microbial growth. In addition, water from natural sources contains nutrients from the breakdown of naturally occurring organic material. Unless this bioactivity is controlled the efficiency of the heat exchanger will be seriously reduced.

1.3 Biofouling and safety consequences of nuclear power plants

Many nuclear power plants have experienced fouling in their cooling water systems (Satpathy, 1996). These fouling incidents have caused flow degradation and blockage in a variety of heat exchangers and coolers served directly by raw water. In addition, loose shells from dead organisms are carried by the flow until they are trapped or impinged in small piping, heat exchangers, or valves. Often the results of fouling that have accumulated behind inlet valves and in heat exchanger water boxes degrade or compromise the safety function of safety-related components. Events of this nature have occurred at several nuclear plants, which prompted the Nuclear Regulatory Commission of USA to issue warning requiring plants to determine the extent of biofouling and to outline their strategy for controlling it (Henager et al., 1985). A few typical incidents reported in the literature are outlined here. Brunswick power plant I and II reported blockages of their Residual Heat Removal (RHR) heat exchangers in 1981 (Imbro and Gianelli, 1982) by American oyster (*Crassostrea virginica*) shells. This produced high differential pressures across the divider plate and caused the plate to buckle. The result was a total loss of the RHR system. The plant was forced to provide alternate cooling. American oysters had accumulated in the inlet piping to the RHR heat exchangers, because the chlorination had been suspended for an extended period. RHR heat exchangers at Unit II were also fouled and severely plugged. The Salem II (S.M. Stoller Corp. 1983) and the Arkansas Nuclear I power plant have reported flow blockages to containment fan cooling units (plugging a backpressure control valve, which restricted flow in the containment fan cooling units) and fouling of containment cooling units respectively (Nuclear Regulatory Commission, 1984, Haried, 1982). Blue mussel shells deposits in the water jacket cooler of a diesel generator at Salem I & Millstone II plant caused the generator to overheat and subsequently trip off (S. M. Stoller Corp. 1977). An industrial processing plant experienced severe Asiatic clam (*Corbicula fluminea*) fouling in its fire protection lines because of frequent flow testing at reduced flow rates. When full flow testing was initiated after several years of operation, the sudden flow surge caused severe blockage in the main and branch piping (Neitzel et al., 1984). Fouling in fire protection systems by Asiatic clam has also been reported at Browns Ferry (Tennessee Valley Authority, 1981) and McGuire power plant (Duke Power Co., 1981). The main condenser at Browns Ferry 1 was severely fouled with Asiatic clams only a few months after the plant began operation in 1974 and the problem increased subsequently (Rains et al., 1984). At Pilgrim I power plant, blue mussels blocked cooling water flow and caused an increase in differential pressure across the divider plates, forcing the plates out of position leading to loss of Reactor Building Closed Cooling Water (RBCCW) heat exchanger capacity (Imbro, 1982). At Trojan power plant, Asiatic clams plugged one of the heat exchangers that cool the lubricating oil to the main turbine bearings (Portland General Electric Co., 1981). Temporary stoppage of normal preventive maintenance during an extended plant shutdown at San Onofre I power plant allowed barnacles (*Pollicipes plymerus*) to incapacitate a component cooling water heat exchanger (Henager et al., 1985). In the same plant a butterfly valve malfunctioned on the seawater discharge side of the cooling water heat exchanger because massive growth of barnacles had reduced the effective diameter of the pipe and impeded valve movement (Henager et al., 1985). In September 1984, St. Lucie power plant reported plugging of its intake screens by Jellyfish (Henager et al., 1985). In August 1983, Calvert Cliffs I power plant tripped manually to avoid an automatic turbine/ reactor trip due to low condenser vacuum, which was the result of shutting down two of six circulating cooling water pumps because their inlet screens had become plugged with fish (Nuclear Regulatory Commission, 1984).

1.3.1 Events that could exacerbate fouling

Some of the non-fouling events could cause a normal bifouling situation to become serious. Generally they are three types; 1) environmental events that affect fouling populations within the plant and in the vicinity of the plant, 2) plant operating events or procedures that may dislodge or kill fouling organisms, and 3) biofouling surveillance and control procedures that may exacerbate fouling.

a. Environmental Events

The following environmental events could occur at nuclear power plants site and affect safe plant operation. Dynamic shocks due to seismic activity, explosions (intentional and accidental), or similar events could loosen fouling organism from their substrate and these can subsequently clog heat exchangers downstream. Heavy rain storms and flooding could wash bivalves from their substrate and carry them into the intake pumps. It can also create a thermal shock which could kill fouling organisms and fish leading to blockage of cooling water systems. Heavy rains also have the potential of creating an osmotic shock due to a rapid decrease in the salinity of the cooling water source resulting in massive killing of fouling organisms. Toxic chemical spills (pesticides, herbicides, industrial chemicals, oil, etc.) due to tanker spills and leakage of pipe line upstream of the plant could kill fouling organisms in the cooling water source and within the plant.

b. In-plants

Some transients and operating procedures that occur during the operation of nuclear power plants can affect biofouling. Although, most of these procedures are necessary, however, several improvements could be made to eliminate or reduce biofouling events associated with these procedures. The following in-plant events have occurred at nuclear power plants leading to dislodge or movement of fouling organism. Sudden changes in flow velocity (increases in velocity) have washed accumulations of bivalves into heat exchangers. Changes in flow direction may also cause bivalves to move into areas with higher velocity from where they can be swept downstream. Sudden gush of cooling water (Water hammer) has been implicated as a cause of heat exchanger clogging at Arkansas Nuclear I plant (due to dislodging of Asiatic clams) and at the Brunswick plant (American oysters) allowing them to be swept into their Residual Heat Removal heat exchangers (Harried, 1982). Thermal shock from either a rapid cooling or heating of the raw water can kill bivalves. At pilgrim power plant, the inadvertent routing of heated water into the service-water intake structure from a condenser backwashing operation caused a massive kill of blue mussels in the intake structure and in the service-water headers (Satpathy et al., 2003). The plant was forced to reduce power to 30% while blue mussels continued to break loose and plug the Reactor Building Closed Cooling Water (RBCCW) heat exchangers. This continued for approximately 3 months. Allowing bivalve shells to accumulate in the intake structure and in areas of the raw-water system encourages clogging and lead to reduced suction head and vortexing problems in the circulating water and service-water. It was reported that accumulations of Asiatic clam shells and silt up to 90 cm (3 ft) deep are not uncommon in the intake structure (Satpathy et al., 2003). Blue mussels have also been described as forming 1.2-m-thick (4-ft-thick) mats on the walls of intake structures (Henager et al., 1985). Starting up of inactive systems has led to clogging when precautions were not taken to prevent bivalves from entering and growing in those systems. The initial flow surge through the system can carry loose bivalves and shells into constricted areas downstream. Chronic fouling has been reported in raw-water cooling loops that are used infrequently (Henager et al., 1985).

Chemical such as diesel oil, lubricating oil, and other toxic chemicals used at nuclear plants could spill in the intake structure and kill fouling organisms. Pump cavitation from plugged suction lines to the pumps would result in increased wear and decreased performance of service-water booster pumps and the main pumps in the fire protection system. The vibration of lines associated with cavitating pumps may also dislodge bivalves and cause fouling downstream. Flushing fouling organisms into drains and sumps could cause plugging and subsequent flooding of equipment rooms. This could damage electrical equipment such as pump motors, electronic instrumentation, and motor-controller valves. Leaking valves have allowed the continuous flow of water to carry food and oxygen to bivalves. Several utilities indicate this as a major cause of fouling in plants (Henager et al., 1985). The same effect may occur in lines where valves are inadvertently left in the semi-opened position. Near stagnant conditions in water systems provide ideal conditions for bivalve growth. This is especially true for Asiatic clams. Most plants typically operate with nearly 80% of the cooling loops in this condition (Neitzel et al., 1984) in order to maintain redundant cooling loops in standby condition. Damaged or missing intake screens and strainers have allowed adult organisms to be sucked into the cooling water system. Also, severe plugging from weeds, grass, and ice have caused the automatic strainer wash systems to malfunction at Salem 1 plant (S.M.Stoller Corp. 1978) and at Indian Point 3 plant (S.M. Stoller Corp. 1983).

c. Surveillance and control procedures

Biofouling control techniques can be divided into two major categories, detection / surveillance and control / prevention programs. Surveillance refers to detecting the biofouling and the subsequent flow degradation. The goal of control techniques, however, is to limit biofouling to a safe and acceptable level. Surveillance and control procedures could cause organisms to flourish or to become dislodged (Daling and Johnson, 1985). Thermal backwashing, although an effective method of killing bivalves, can result in enhanced clogging of heat exchangers when measures are not taken to remove the bivalves that are killed. It is also important to account for the time lag between the thermal treatment and the detachment of the bivalves. This is especially true for blue mussel and American oyster fouling. Thermal backwashing should be scheduled to prevent bivalves from growing large enough to block condenser tubes. Similarly, when shock chlorination is used to kill the established community and subsequently care is not taken to remove them, they accumulate and clog downstream (**Fig. 1**).

Fig. 1. Removed fouling organisms from the tunnel of a seawater cooled nuclear power plant (Madras Atomic Power Station) by shock chlorination

Increased flow rates during testing can wash bivalves into heat exchangers. This is especially true of Asiatic clam fouling because adults lose the ability to attach to substrates and will be flushed into downstream heat exchangers at increased flow rates. The initial flow testing or flushing of a stagnant, infested line has led to an unexpectedly large number of bivalves which occurred at Browns Ferry 1 power plant, when the condenser circulating water system was started up after construction was completed. An intermittent chlorination system that malfunctioned and released a massive dose of chlorine to the intake killed large numbers of bivalves. These bivalves later detached and clogged heat exchangers. The intermittent chlorine application would not control bivalves in the system, but a large chlorine spill may be concentrated enough and last long enough to kill bivalves.
The following enhanced growth events have occurred at nuclear power plants due to procedures or strategies. Infrequent or inadequate chlorination caused by faulty or wrongly calibrated chlorinating metering systems or by intentional, intermittent applications of chlorine have allowed bivalves to survive in raw-water systems. Personnel from several plants remarked that bivalve fouling became worse when the chlorination system was out of service for an extended period. Intermittent chlorination to control slime and other microfouling has been ineffective in controlling bivalves because, they are able to close their shells tightly during periods of chlorination. Failure to chlorinate normally stagnant cooling loops, which already have a high potential for fouling, can substantially increase the fouling potential of the system. Frequent flow testing, particularly if done at low flow velocity, may improve the growth potential of the system by providing a more frequent supply of food and oxygen to bivalves. This effect is intensified if flow testing is not concomitant with chlorination. The intermittent, “non-design” use of the fire protection system to water lawns and wash equipment has also provided enhanced conditions for Asiatic clam growth.

1.4 Biofouling at Madras Atomic Power Station

The best approach to understand biofouling problem in a seawater cooled power plant is by taking a typical example which has been studied well. The Madras Atomic Power Station (MAPS) located at Kalpakkam (12˚ 33″ N; 80˚ 11″ E) consists of two units of Pressurized Heavy Water Reactor (PHWR), each of 235 MW (e) capacity. Seawater is used at the rate of 35 $m^3 sec^{-1}$ as the coolant for the condenser and process cooling water systems. A sub-seabed tunnel located 53 m below the bottom terrain draws seawater (**Fig. 2**). The tunnel is 468 m long and 3.8 m in diameter. It is connected at the landward end to the pump house through a vertical shaft of 53 m deep and 6 m diameter called forebay. Similarly, the seaward end of the tunnel is connected to a vertical shaft of 48 m and 4.25 m diameter called intake. Seawater enters the intake through 16 windows located radially at the intake structure, 1 m below the lowest low water spring tide. The tunnel, intake and forebay shafts support a heavy growth of benthic organisms such as mussels, barnacles, oysters, ascidians etc. The high density of these fouling organisms inside the tunnel/cooling systems could be attributed to continuous supply of oxygen & food and removal of excretory products by the passing seawater providing a conducive environment for their settlement and growth. In addition, absence of any potential predator inside the cooling system supports a luxuriant growth of these communities. The physical shape of the tunnel is such that it is an isolated system open at both ends; seawater samples can be collected at intake as the control location, whereas, samples collected at forebay after flowing past the fouling communities can be investigated for change in its physicochemical properties.

Biofouling in the cooling system of seawater-cooled power plants is a universal problem (Brankevich et al., 1988; Chadwick et al., 1950; Collins, 1964; Holems, 1967; James, 1967; Relini, 1980; Satpathy, 1990). It is of considerable interest as it imposes penalty on power production, impairs the integrity of cooling system components and in some cases even precipitates safety problems associated with cooling system of nuclear power plants (Henager et al., 1985; Rains et al., 1984), which has been already discussed. Different aspects of biofouling in the cooling conduits of coastal power plant from tropical as well as temperate regions have been studied by several researchers (Brankevich et al., 1988; Chadwick et al., 1950; Collins, 1964; Holems, 1967; James, 1967; Relini, 1984; Satpathy, 1990; Sashikumar, 1991). The problem of biofouling in a tropical seawater cooled power plant can be understood by explaining a typical case study. Studies carried out in this regard from Indian coast have not been exhaustive however, from Kalpakkam coast, south east coast of India, it has been immense due to its importance to the existing MAPS. Biofouling has been a serious problem in the cooling water system of MAPS. It had affected adversely the cooling system and performance of the plant (Sashikumar, 1991; Rajagopal, et al., 1991; Satpathy et al., 1994). Investigation on the fouling problems of MAPS cooling system indicated extensive settlement of macro-fouling organisms inside the tunnel, which was calculated to be around 580 tonnes (Nair, 1985) that caused severe pressure drops in the cooling circuits.

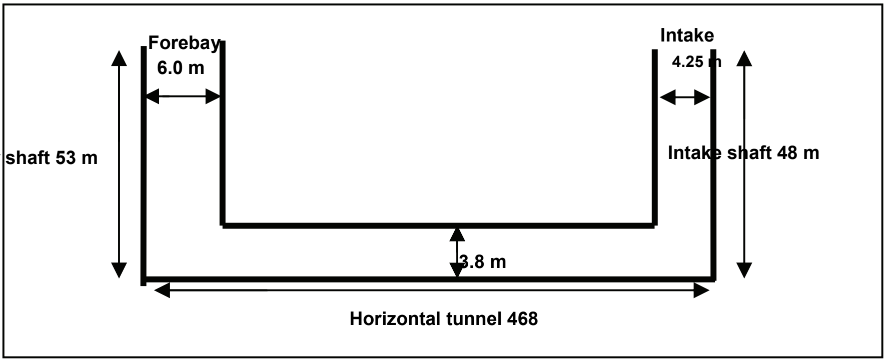


Fig. 2. Schematic diagram of the cooling water structure of MAPS

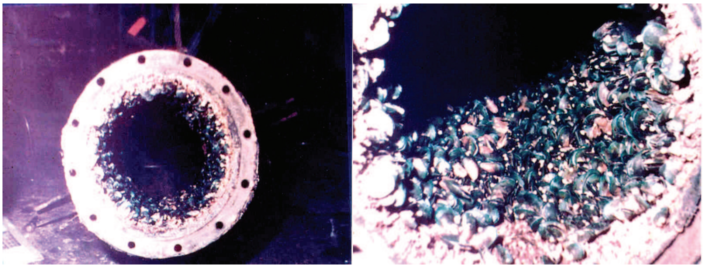
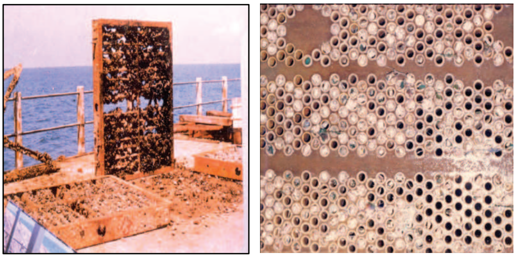


Fig. 3. A view of bio-growth inside seawater pipe lines from MAPS

The intake submarine tunnel was observed to have a maximum of 25 cm thick layer of fouling organism with an average of 18 cm (Satpathy et al., 1994). A typical blockage of a cooling water pipe is shown in **Fig. 3**. In addition stupendous growth of fouling organisms on the intake screen (**Fig. 4a**) of MAPS impedes its smooth operation (Satpathy, 1996). The condenser tubes of MAPS were severely affected by the clogging of dead green mussel (**Fig. 4b**) (Satpathy, 1996). Similarly, jelly fish ingress and clogging of intake and traveling water screen forcing the plant authorities to shut down the reactor (Masilamani et al., 2000), has been another problem. Albeit, it is a seasonal issue, it also plays havoc with the operation of the cooling water system and ultimately power plant operation.



(a) (b)

Fig. 4. Blockage of intake screen by fouling organisms (a) and blockage of condenser tubes by green mussels & barnacles (b)

2. Description of the locality

Kalpakkam coast (12° 33' N Lat. and 80° 11' E Long.) is situated about 80 km south of Chennai (**Fig. 5**). At present a nuclear power plant (MAPS) and a desalination plant are located near the coast. MAPS uses seawater at a rate of 35 m^3sec^{-1} for condenser cooling purpose. The seawater is drawn through an intake structure located inside the sea at about 500 m away from the shore. After extracting heat, the heated seawater is released into the sea. Two backwaters namely the Edaiyur and the Sadras backwater system are important features of this coast. These backwaters are connected to the Buckingham canal, which runs parallel to the coast. Based on the pattern of rainfall and associated changes in hydrographic characteristics at Kalpakkam coast, the whole year has been divided into three seasons viz: 1) Summer (February-June), 2) South West (SW) monsoon (July-September) and 3) North East (NE) monsoon (October-January) (Nair and Ganapathy, 1983). Seasonal monsoon reversal of wind is a unique feature of Indian Ocean that results in consequent change in the circulation pattern (La Fond, 1957; Wyrtki, 1973), which is felt at this location too. The wind reversal occurs during the transition period between the SW monsoon and NE monsoon. In general, the SW to NE monsoon transition occurs during September/ October and the NE to SW transition occurs during February/ March. The pole-ward current during SW monsoon changes to equator-ward during the SW to NE monsoon transition, whereas, a reverse current pattern is observed during the transition period between NE to SW monsoon (Varkey et al., 1996; Vinaychandran et al., 1999; Haugen et al., 2003). Subsequent to the change in the current pattern, the alterations of coastal water quality have been reported (Somayajulu et al., 1987; Ramaraju et al., 1992; Babu, 1992; Saravanane, 2000). The phenomenon of upwelling has also been reported to occur during the pre-NE monsoon period in the southeast coast of India in low temperature and high saline water mass (De Souza et al., 1981; La Fond, 1957; Ramaraju et al., 1992, Suryanarayan and Rao, 1992). During the period of NE monsoon and seldom during SW monsoon monsoon, the two backwaters get opened to the coast discharging considerable amount of freshwater to the coastal milieu for a period of 2 to 3 months. This part of the peninsular India receives bulk of its rainfall (~ 70%) from NE monsoon. The average rainfall at Kalpakkam is about 1200 mm. However, with the stoppage of monsoon, a sand bar is formed between the backwaters and sea due to the littoral drift, which is a prominent phenomenon in the east coast of India, resulting in a situation wherein the inflow of low saline water from the backwaters to sea is stopped. This location had been badly affected by 2004 mega Tsunami, which devastated the entire east coast of India and had maximum impact at this part of the coast.

Fig. 5. A map of the study area, Kalpakkam coast, Bay of Bengal

The mean tidal range varied from 0.3 – 1.5 m. The coastal currents at Kalpakkam has seasonal character and during SW monsoon the current is northerly (February to October) with a magnitude of 0.2 – 1.8 km/h and during NE monsoon the current is southerly (October to February) with a magnitude of 0.1 – 1.3 km/h. The wind speed varied from 10-40 km/h. These monsoonal winds cause a) southerly (~ 0.5 million m^3/y) & northerly (~ 1 million m^3/y) littoral drift (Satpathy et al., 1999). The seawater temperature has two maxima (Apr/May & Aug/Sept) and two minima (Dec/Jan & June/July) (Satpathy and Nair, 1990; Satpathy et al., 1999; Satpathy et al., 1997).

3. Hydrobiological features of coastal waters

3.1. Methodology

Seawater samples were collected weekly near the MAPS cooling water intake for estimation of water quality parameters such as pH, salinity, dissolved oxygen (DO), turbidity, chlorophyll-*a* and nutrients such as, nitrite, nitrate, ammonia, total nitrogen, silicate, phosphate and total phosphorous. Water temperature was measured at the site using a mercury thermometer of ±0.1 ^{0}C accuracy. Salinity was measured using Knudsen's method (Grasshoff et al., 1983). Estimation of DO was carried out following the Winkler's method (Parsons et al., 1982). pH was measured using a pH probe (Cyberscan PCD 5500) with accuracy of ±0.01. Turbidity was measured using Turbidity meter (Cyberscan IR TB100) with accuracy of ±0.01 NTU. Chlorophyll-*a* and nutrients were analyzed following the standard methods of Parsons et al. (1982) using a double beam UV visible spectrophotometer (Chemito).

3.2 Results

Hydrographical parameters at this coast bear pronounced seasonal variations (Satpathy et al., 2008, 2010). Temperature varies from 26.0 (August) to 31.8 ^{o}C (May) indicating that the annual gradient remained ~5.8 ^{o}C. Seawater temperature is characterized by two maxima, one during April/ May and another during September/ October coinciding with the trend in atmospheric temperature. pH values ranged between 8.00 and 8.30 with maximum value during NE monsoon period. Salinity ranged from 24.91 (November) – 35.90 psu (May), which showed a unimodal oscillation. Dissolved oxygen (DO) values fluctuated between 4.2 and 6.1 mg l^{-1}. Values of turbidity varied between 9.21 and 21.42 NTU. Chlorophyll-*a* concentration varies between 1.42 and 7.51 mg m^{-3} during the month of November and August respectively.

The maximum value of pH observed, coincides with NE monsoon period during which not only the precipitation, but also the discharges from the nearby backwaters affect the magnitude of pH as well as salinity significantly. As expected, the lowest salinity value coincides with the local maximum precipitation period (NE monsoon period) and also with the maximum influx of fresh water from the two nearby backwaters. The highest salinity value coincides with the peak summer. DO shows an irregular pattern of distribution except for the fact that during NE monsoon period, relatively high values are observed as expected due to input of oxygen rich freshwater. Turbidity exhibits a bimodal oscillation with one peak during July (pre-monsoon) and another during December (NE monsoon). This is attributed to the relatively high phytoplankton density observed during pre-monsoon and heavy silt-laden freshwater influx during NE monsoon seasons. A significant positive correlation ($p \geq 0.01$) between turbidity and chlorophyll has been observed and is testimony to the above observation during pre-monsoon period (Satpathy et al., 2010). Chlorophyll-*a* values are found to be the lowest during November/ December (NE monsoon) and highest during August/ September (Southwest-Northeast monsoon transition). Relatively high concentration of chlorophyll-*a* coincides with summer and pre-monsoon period, when relatively stable as well as optimal conditions of salinity, temperature, light, nutrient levels (conducive for production of copious amount of phytoplankton) prevails. Depletion of chlorophyll concentration during monsoon period is mainly associated with low saline, low temperature, low irradiance and high turbidity condition.

Nutrient concentrations in general show well pronounced seasonal variation mostly influenced by monsoonal rain. The two back waters, which are part of the ecosystem at this location, receive various wastes (domestic, agricultural etc.) from the nearby township and villages and thereby get enriched with nutrients. These backwaters get open to the coastal water during the NE monsoon period resulting in influx of the nutrient rich fresh water into the coastal milieu, which enhances the nutrient levels in the coastal water. Relatively low values are observed during pre-monsoon and post- monsoon period (April-August) which is attributed to their utilization by phytoplankton, as evident from the matching chlorophyll values during the same period. Increased levels of phosphate is also observed during September which has been associated with the phenomenon of upwelling, an event that generally occurs during pre-monsoon (August – September) period along the Indian east coast (La Fond, 1957; De Souza et al., 1981; Ramaraju et al., 1992; Suryanarayan and Rao, 1992).

4. Biofouling potential of Kalpakkam coastal waters

A close perusal of literature on biofouling studies point that they have been triggered mainly based on two sound logics, such as scientific interest or technological need associated with maritime activities. The methodology such as, size of panel, duration of exposure, panel material, location of exposure etc used for biofouling studies largely remain similar by many workers. Researchers with academic interest look for ecological succession, species diversity, breeding pattern, seasonal variations, larval availability, climax community, that is more towards qualitative assessment and linking them with environmental factors. However, investigations with technological need look for quantitative assessment such as, biomass, % of area coverage, density and occurrence interval. Notwithstanding the interest driven by either, the three important parameters for practical use undoubtedly are a) type of foulants, b) their growth rate and c) their seasonal variations, which decides the use of an economic and environment-friendly fouling control strategy. Biofouling problem is not only site specific, but also have been reported to be different for two different power plants drawing same source of cooling water (Karande et al., 1986), which has been attributed to different design and different material of use. An evaluation of composition and abundance of the fouling communities available in coastal waters provides an array of information particularly for the effective antifouling measures to be adopted in the cooling water systems.

In order to devise an effective biofouling control measure for Prototype Fast Breeder Reactor (under construction) cooling water system, it is essential to evaluate the present biofouling potential at Kalpakkam coastal waters. Considering a big hiatus lapsed between the last study (almost 20 years old) and the present need, a study was carried out with the following objectives; to find out a) the present seasonal settlement pattern of biofoulers, dominant species and breeding pattern, b) any change, as compared to that of earlier reported data and c) the role of physico-chemical characteristics of coastal water on biofouling. Moreover, this coast was severely affected by 2004 tsunami. Thus, the present study also brings out any change in settlement pattern, diversity, biomass and population density between pre- and post-Tsunami period.

4.1 Material and Methods

The present study was carried out between May 2006 to April 2007, in the coastal waters of Kalpakkam in the vicinity of MAPS. The study area is located at the intake of MAPS Jetty. Water depth at the study site is ~8 m. Teak wood panels (each 12 x 9 x 0.3 cm) were suspended on epoxy coated mild steel frames from MAPS jetty. The panels were suspended at 1 m below the lowest low water mark, approximately 400m away from the shoreline. Three series of observations (weekly, monthly and cumulative at 30 d intervals) were made.

Weekly & monthly observations were considered under short-term observations and cumulative was considered under long-term observation. Two unique features of this study are, for the first time a) fouling data at an interval of 7d is available and b) photographs of each series are digitally available for future comparison. Different evaluating parameters viz. composition of organisms, number of organisms, growth rate, both % of number and % of area coverage, biomass (g. per 100 sq. cm) were used to study the fouling pattern. Fouling concentration was assessed by counting the foulants available on the panels. Total biomass was calculated using a correction factor due to the absorption of water by the panels for specified time periods. The growth rate was recorded by measuring the size of macrofoulers. Apart from the above-mentioned parameters, diversity indices such as species diversity (D), species richness (R) and evenness (J) were also calculated following Shannon-Weaver (1963), Gleason (1922) and Pielou (1966).

4.2. Results

4.2.1. Fouling Community

A list of organisms collected from test panels are given in **Table 1**. The total number of taxa involved in the fouling process at Kalpakkam coastal waters are found to be 30 during the present investigation.

4.2.2. Biomass

Biomass values of weekly panels ranged from 1-11 g. per 100 sq. cm **(Fig. 6a)**. The lowest and highest biomass values for weekly panels were obtained in the months of November and December respectively. In the monthly observation, the lowest (17 g. per 100 sq. cm) and the highest (46 g. per 100 sq. cm) were observed in April and November respectively **(Fig. 6b)**. In case of cumulative panel, a steep increase in biomass was observed from 28 d (77 g. per 100 sq. cm), 56 d (97 g. per 100 sq. cm), 112 d (185 g. per 100 sq. cm) to 150d (648 g. per 100 sq. cm) **(Table 2)** onwards.

4.2.3. Settlement pattern in short-term (weekly and monthly) panels

A wide variation was observed in the number of settled organisms on weekly panels. Major fouling organisms observed were barnacles, hydroids, ascidians, oysters, sea anemones and green mussels. In addition to these sedentary organisms, some epizoic animals like errant polychaetes, flat worms, amphipods, crabs were also observed. Number of fouling organisms, number of species and % of area coverage are given in **Table 2**.

Coelenterata

Campanulariidae	*Obelia bidontata* **Clarke**
	Obelia dichotoma **Linnaeus**
	Clytia gracilis **M.Sars**
Aiptasiidae	*Aiptasia* sp

Annelida

Nereidae	*Pseudonereis anomala* **Gravier**
	Platynereies sp

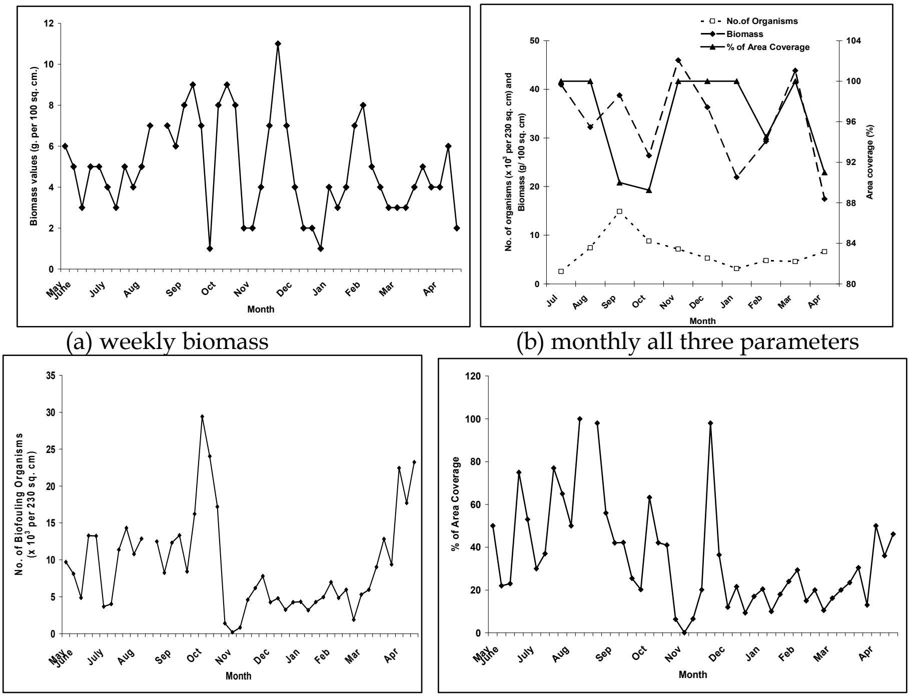
Serpulidae	*Serpula vermicularis* **Linnaeus**
	Hydroides norvegica **Gunnerus**
Sabelidae	*Daychone* sp
	Sabellistarte sp
Arthropoda	
Pycnogonidae	*Pycnogonium indicum* **Sunder Raj**
Balanidae	*Balanus amphitrite* **Darwin**
	Balanus reticulatus **Utonomi**
	Balanus tintinnabulum **Linnaeus**
	Balanus variegatus **Darwin**
Corophidae	*Corophium madrasensis* **Nayar**
	Corophium triaenonyx **Stebbing**
Amphithoidae	*Paragrubia vorax* **Chevreux**
Ectoprocta	
Membraniporidae	*Menbranipora* sp
Electridae	*Electra* sp
	Acanthodesia sp
Mollusca	
Mytilidae	*Perna viridis* **Linnaeus**
	Perna indica **Kuriaose**
	Modiolus undulatus **Dunker**
Olividae	*Olivancillaria gibbosa* **Born**
Ostreidae	*Crassostrea madrasensis* **Preston**
	Ostrea edulis
	Saccostrea cucullata **Born**
Urochordata	
Didemnidae	*Didemnum psammathodes* **Sluiter**
	Lissoclinum fragile **Van Name**

Table 1. List of fouling organisms observed on the test panels suspended in the Kalpakkam coastal waters

The lowest and the highest numbers of foulants for weekly panels were 1 (November) and 136 per sq. cm (October) respectively **(Fig. 6c)**. Fouling intensity was relatively high during summer and SW monsoon period, whereas during NE monsoon period, negligible intensity was observed. In monthly observation, the maximum (69 per sq. cm) and the minimum (12 per sq. cm) population density were obtained in September and January respectively **(Fig. 6b)**. From July to September (SW monsoon) an increasing trend was observed, whereas from October onwards (NE monsoon) the fouling intensity started declining. Once again after January the fouling density was found to increase. This almost followed the salinity variation pattern observed for this coastal water. The percentage (%) of area coverage on weekly panels showed a well marked variation ranging between 0.08 and 100% **(Fig. 6d)**, whereas, in case of monthly observation, it was found to be 89 – 100%. In monthly observation, maximum area coverage (100%) was found during July -August, November – January and March **(Fig. 6b)**. However, during weekly survey, maxima (80 - 100%) were attained in August – September and November.

4.2.4. Variation in seasonal settlement of fouling organisms

Barnacle: Among the different groups, barnacles were found to be the most dominant fouling community and its accumulation on the test panels was observed throughout the year. During the present study period, barnacles were represented by four species such as, *Balanus amphitrite*, *B. tintinabulum*, *B. reticulatus* and *B. variegatus*, which were found to be the most dominant on weekly (12.4 - 99%) as well as monthly (5.9 – 85.2 %) panels. On weekly panels, barnacle settlement was continuous with peaks observed during June-July and November –March. In case of monthly panels, large numbers were observed during July, November-December and March–April. During weekly and monthly observation maximum growth (size) obtained were 0.5-1 mm and 2-3 mm respectively.



(a) weekly biomass (b) monthly all three parameters

(c) weekly no. of organisms (d) weekly area coverage

Fig. 6. Variations in no. of organisms, biomass and % of area coverage on weekly and monthly panels

Hydroids: Hydroids were only second to barnacles in abundance as well as seasonal occurrence and were dominated by *Obelia* sp. They started appearing on the panels after 5d immersion. The growth of hydroids was recorded by measuring the length from base to tip. A maximum length of 5 mm on weekly panel and 17 mm on monthly panel was observed. Its % composition varied between 0.64 & 81.62 % and 1.66 & 37.28 % during weekly and monthly investigation respectively.

Ascidians: *Didemnum psammathodes* and *Lissoclinum fragile* were the ascidian species encountered during the present observation. In the weekly observation, the occurrence of ascidians was generally restricted to March-April and June – August, with peak settlement during March-April. Monthly observation also depicted the dominance of ascidians during March-April and June-July, but with maximum density during June.

Sea anemones: Sea anemones, also a prominent group among the fouling assemblages, were represented by *Sertularia* sp., *Aiptasia* sp. in both weekly as well as monthly observations. They were found settling from Sepetember/ October onwards and formed a group particularly abundant during NE monsoon period. Their rate of growth was 1.5 mm diameter in 7 d and 8 mm diameter in 30 d observation and the settlement was relatively less during SW monsoon period.

Green Mussels: Green mussels (*Perna viridis*) were the most important constituent of the fouling community. They were mostly found attached to the mild steel frames during short-term investigation and their absence was encountered during the entire weekly observation. However, during monthly survey, their % composition varied from 0.08 – 11.02 % and their colonization was generally observed during May-September with vigorous settlement during May-June and August – September.

4.2.5. Seasonal settlement on long -term (cumulative) panels

During the present observation, long -term panels were studied up to 150 days after which panels were lost due to entanglement of the frames and could not be retrieved. In the Kalpakkam coastal waters considerable settlement of barnacles, green mussels and ascidians were observed on the long-term panels. Apart from that, colonization of hydroids, oysters and sea anemones was also observed on the long-term panels. In addition to these sedentary organisms, epizoic animals like errant polychaetes, flat worms, amphipods, crabs were also observed. Peak settlement period of foulants, succession and climax community are represented in **Table 2**. Fouling succession was very prominent during the long-term observation as compared to weekly and monthly observation. Barnacles were the first to settle on the long-term panels and by the time they were of 14 mm in size, they were followed by hydroids and polychaete worms during the month of May. During this period, barnacle population remained largely unaffected by the secondary settlers. Ascidians began to colonize on the panels from June. Fully developed ascidian colonies completely covered the barnacles and other organisms by July and they remained till the end of August. Disappearance of ascidians was noticed from the month of September. Green mussels started appearing from August, whereas the peak colonization of mussels was observed from September onwards and it was maintained till mid-November.

Percentage composition of barnacles initially increased upto 56 d and subsequently reduced significantly on the long-term panels as follows (15%, 28%, 13% and 5% on 28 d, 56 d, 112 d and 150 d old panel respectively). Green mussel, which was absent upto 28 days, started appearing subsequently and occupied 41% by 56d and reached 90% by 150d. Accumulation of juvenile green mussels occurred after 28 days along with the pre-existing community consisting of barnacles, hydroids, oysters, polychaete worms, flat worms & sea anemones. The mussels attained 0.5-1 cm in size by 56 d and from 112 d onwards, the panels were fully covered with adult green mussels of size 3 - 5 cm. **(Fig. 7)**. The relative abundance of fouling community observed for 28 d, 56 d, 112 d and 150d are given in **Fig. 8**.

	Nair et al. , 1988	Sashikumar et al., 1989	Sashikumar et al., 1990	Rajagopal et al., 1997	Present study		
					Weekly	**Monthly**	**Cumulative**
No. of organisms (x 10^3 per 230 sq. cm)	----	----	----	----	(0.185-29) x10^3	(2 –15) x 10^3	(0.166– 63) x10^3
No. of species	----	21	----	105	30		
% of Area coverage	----	62 (Dec.)–100% (Jul.-Aug) - Monthy	53 (Nov.)-100% (Apr.,Jul.- & Aug.) - Monthy	34 (Feb.)–72% (Oct.)-Monthy	0.08 (Nov.)-100 % (Aug.)	89 (Oct.)–100% (Jul./Aug.)	100%
Biomass (g/ 100 sq. cm)	43 d -33;128d – 52; 150 d– 135	56d -90;120d –105; 150d –1000	45d – 32; 60d – 52; 130d– 50; 160d – 138	56d –750; 125d -1870; 150d – 1750	1 –11	17 – 46	28d - 77; 56d -97; 112d –185; 150- 648
Peak settlement	Barnacles (Mar.-Jul.) Hydroides (Feb. – Aug.) Ascidians- May Sea anemone (Sep. – Oct.) green mussels– September onwards	Barnacles (throughout the year) Hydroides (Feb. – Nov.) Ascidians (Mar. –Aug.) Sea anemone – NE monsoon	Barnacles (Throughout the year) Hydroides (Mar. –Apr. & Sep.) Ascidians (Apr. - Aug.) Sea anemone (Feb. - Oct.)	Barnacles (throughout the year) Green mussels (Apr. – Aug.)	----	----	Barnacles (Mar. – Jul.) Green Mussel (*Perna viridis*)- (Sep.-Nov.)
Diversity indices SD SR E	----	----	1.21(125d)–1.69 (75d) 0.04(150d) - 0.11(65d)	----	SD (0.05-0.96) SR(0.11–0.69) E (0.08 – 0.99)	SD(0.5-1.55) SR(0.45-1.0) E (0.26-0.74)	0.43(150d) –1.60(56d) 0.36(150d) –0.80(56d) 0.31(150d) –0.73(56d)
Succession	Barnacles, hydroides sea anemone, ascidians, green mussels	Barnacles, hydroides ascidians, sea anemone, green mussels	Barnacles, hydroides, ascidians, sea anemones, green mussels	Barnacles, ascidians, green mussels	----	----	Barnacles, hydroides, sea anemone, Ascidians, green mussels
Climax community	Barnacles	Green Mussel (*Perna viridis*)	Ascidians	Green Mussel (*Perna viridis*)	----	----	Green mussels

Table 2. Comparison of present fouling data with earlier reported values