Chlorination and Mussel Control in the Cooling Conduits of a Tropical Coastal Power Station

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ABSTRACT

The rationale for the present study has been the continued problem of biofouling in the cooling conduits of Madras Atomic Power Station (Kalpakkam), in spite of intermittent chlorination used as a fouling control measure. A diver-assisted inspection of the tunnel proved that the green mussel, Perna viridis (L.) was the major component of the fouling community inside the cooling conduits. Maximum biomass value recorded was 211 kg/m², observed inside the forebay shaft at a depth of 22.5 m. The total biomass of fouling in the entire tunnel system was estimated to be 578 tonnes, of which the contribution by P. viridis alone was 411 tonnes. High-level chlorination, followed by continuous low-level chlorination brought large quantities of sessile biomass from the tunnel to travelling water screens (TWS). A total biomass of about 187 tonnes of fouling debris was collected from TWS during February 1988 to January 1990. Of these, P. viridis accounted for 164 tonnes. The size-frequency distribution of P. viridis collected on the TWS clearly showed that the appearance of young mussels (0–2 cm shell length) was correlated with the breeding pattern of green mussels in the adjacent coastal waters. The present study showed that intermittent chlorination is an ineffective method for mussel control in the power station cooling conduits. Continuous high-level chlorination is useful for dislodging established mussel communities from intake tunnels.

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INTRODUCTION

Most nuclear power stations are strategically placed in close proximity to the sea, with a view to making use of the cheap and abundant source of seawater as a heat sink. Settlement and growth of fouling organisms in the cooling systems of these stations often constitutes a problem of considerable economic significance (Jenner, 1980; Brankevich *et al.*, 1988). Four categories of biofouling-induced problems in power stations can be distinguished: blockage of free flow of water in the cooling conduits and consequent mechanical damage to pumps (Neitzel *et al.*, 1984), clogging of condenser tubes (Henager *et al.*, 1985), reduction in heat transfer efficiency (Rajagopal *et al.*, 1994a) and acceleration of corrosion (Fischer *et al.*, 1984). Apart from this, fouling in nuclear power stations has the potential to affect raw water systems including back-up cooling loops provided for safety-related cooling systems (Neitzel *et al.*, 1986). Although the problems outlined above are likely to be encountered in any power station using seawater as a coolant to a greater or lesser extent, comprehensive studies in this area are surprisingly very few (Graham *et al.*, 1975; Jenner, 1982; Lewis, 1985; Rajagopal, 1991).

Madras Atomic Power Station (MAPS) is situated 65 km south of Madras on the east coast of India. MAPS experienced severe pressure drop beyond the station's operational design limit in the forebay (Nair, 1990), and flow blockage (by mussel shells) in the condenser tubes due to heavy growth of calcareous fouling organisms in the cooling systems (Rajagopal *et al.*, 1991a). The station operators, prompted by such fouling-induced flow-reduction, conducted diving inspections of the seawater intake tunnel with the help of a Remotely Operated Vehicle (ROV). The samples collected by divers and ROV photographs showed extensive growth of fouling organisms, dominated by green mussel, *Perna viridis* (L.) in the sub-seabed tunnel. After tunnel inspection, MAPS switched over to high-level chlorination in January 1988 to dislodge the excessive growth of mussels, followed by continuous low-level chlorination to control recolonization and maintain satisfactory flow of cooling water.

The present paper focuses on the problem of flow-reduction due to biofouling, the relative biomass and composition of different fouling organisms at various depths from the divers' collected samples, the chlorination schedule used to remove excessive biofouling growth and data on the subsequent removal rate of different foulants from MAPS intake tunnel. Attempts have also been made to confirm the relationship between removal of fouling debris and seawater volume transport in the cooling conduits of MAPS.

MATERIALS AND METHODS

Site description

Madras Atomic Power Station (MAPS) consists of two units, each with an installed capacity of 235 Mw (e), and is situated at Kalpakkam (12°33'N and 80°11'E) on the east coast of India. The cooling water requirement for the two units operating at full power is about 35 m³/sec. The seawater cooling system consists of an intake structure, located 420 m away from the shore in the sea (Fig. 1). A tunnel, 468 m long and 53 m below mean sea level (MSL), connects the forebay and the pump house to an intake structure. At the forebay, 12 pumps (6 for each unit) draw seawater and circulate it through the condensers

Fig. 1. Schematic diagram of submarine tunnel of Madras Atomic Power Station (not drawn to scale; + and - signs indicate levels above and below the mean sea level).

and other heat exchangers. The coolant seawater velocity when all the 12 pumps are running, works out to be about 3.5 m/sec in the horizontal section of the tunnel (Madras Atomic Power Station Design Manual, 1975). In the forebay, travelling water screens (TWS) with 1 cm $\times$ 1 cm mesh are used to remove smaller objects before water is pumped to the condensers. For further details of the cooling circuit, refer to Rajagopal *et al.* (1991a). MAPS unit I was commissioned in July 1983; chlorination based on an intermittent schedule (1 to 2 mg/litre residual at outfall for 1 h, once in 8 h) has been in use in the cooling water system as a biofouling control measure since 1979.

The present chlorination practice at MAPS is to bring bulk liquified chlorine in 1 tonne cylinders and inject it by feeding through a vaporiser. The gaseous chlorine from the vaporiser passes through a vacuum regulator. The chlorine injectors suck the chlorine into the down stream of the vacuum injectors. Chlorine is injected into the seawater at the intake point.

Hydrographic conditions

Collection of surface water samples was done at fortnightly intervals. The temperature was measured by a thermometer of 0.1°C accuracy. Salinity was estimated by the silver nitrate method (Strickland & Parsons, 1972). Dissolved oxygen content was measured by Winkler's method and seston by using Millipore filter paper of 0.45 μ m porosity (Strickland & Parsons, 1972). For pH measurement, a digital pH meter (model Kent EIL 3055) was used. Dissolved nutrients (nitrite, nitrate, inorganic phosphate and reactive silicate) and chlorophyll-*a* analyses were carried out following procedures outlined by Parsons *et al.* (1984).

Head loss

Fouling-induced water blockage in the conduit was assessed by determining the water level differences between forebay and intake (head loss). This measurement was done from the platform at the respective places, using a lead and line (Rajagopal *et al.*, 1991b).

Variations in the water level differences are also influenced by the number of pumps operating. With a view to maintaining uniformity, measurements were made only when 11 pumps were operating. A total of 40 measurements were made during 4 March 1986 to 12 March 1990.

Diving inspections

The intake system was inspected using an ROV from 9 to 16 December 1987. Apart from this, a team of divers was employed to collect samples from various parts of the submarine tunnel system. A total number of 19 quadrats (225 cm² each) were sampled. The samples collected by divers were sorted out to species level and biomass (wet weight) of individual species determined. Based on these data, total biomass of different fouling organisms inside the tunnel was calculated (Rajagopal *et al.*, 1991a).

Chlorine doses

After inspection of the tunnel by divers, continuous chlorination of cooling water was started in January 1988. In the initial two months relatively higher doses (shock-doses) were given. Based on the quantity of chlorine added and the volume of water flowing through the tunnel, dose levels were calculated. In addition, actual measurements of total residual chlorine levels in the forebay well were also made using orthotolidine method (White, 1972). Results of biweekly measurements were averaged to obtain mean monthly figures during the period January 1988 to January 1990.

Fouling debris removal from the tunnel

Subsequent to high-level chlorination, fouling debris started coming out of the tunnel along with flowing water. This was collected on the TWS at the forebay. The collected fouling organisms from TWS were transferred to drums (45 or 200 litre capacity). Each day, total number of drums were noted and randomly a few drums were selected for studying the fouling composition. Fouling organisms were sorted out up to species level and later weighed (wet weight) and counted separately for their individual biomass and numerical abundance. Size-frequency distribution of the most dominant species, *P. viridis*, was also determined using random samples. Afterwards, the green mussel shells were sorted out into two categories, i.e. live and dead (based on whether the shells were closed or agape) and weighed separately.

Growth rate

Green mussels growing on the experimental teakwood panels (150 × 100 × 5 mm) suspended in the adjacent coastal waters were collected at monthly intervals and the shell lengths measured to determine their growth rate (Page & Hubbard, 1987).

RESULTS

Hydrographic conditions

Table 1 summarises the data on hydrographical parameters during the study period.

TABLE 1

Seasonal Variations in the Hydrographical Parameters at Kalpakkam Coastal Waters During April 1988 to March 1990. Data are Expressed in Monthly Mean $\pm$ SD

Months	Temperature (°C)	Salinity (‰)	Dissolved oxygen (mg/litre)	pH	Seston (mg/litre)	NO ₂ -N (µmol/litre)	NO ₃ -N (µmol/litre)	PO ₄ -P (µmol/litre)	SiO ₄ -Si (µmol/litre)	Chlorophyll a (mg/litre)
Apr 1988	30.2 $\pm$ 0.4	34.0 $\pm$ 0	5.79 $\pm$ 0.39	8.1 $\pm$ 0	43.7 $\pm$ 16.0	0.05 $\pm$ 0.03	0.81 $\pm$ 0.23	0.07 $\pm$ 0.01	3.75 $\pm$ 0.55	5.06 $\pm$ 0.38
May	30.9 $\pm$ 0.8	35.1 $\pm$ 0.1	4.78 $\pm$ 0.07	8.2 $\pm$ 0.2	34.5 $\pm$ 10.5	0.02 $\pm$ 0.02	1.25 $\pm$ 0.33	0.06 $\pm$ 0.01	6.70 $\pm$ 0.80	9.99 $\pm$ 0.68
Jun	30.2 $\pm$ 0.3	35.5 $\pm$ 0.1	4.54 $\pm$ 0.30	8.2 $\pm$ 0.1	44.4 $\pm$ 6.9	0.04 $\pm$ 0.02	1.77 $\pm$ 0.44	0.09 $\pm$ 0	9.20 $\pm$ 0.50	9.75 $\pm$ 2.62
Jul	28.3 $\pm$ 0.4	34.9 $\pm$ 0.1	4.98 $\pm$ 0.85	8.1 $\pm$ 0.1	29.6 $\pm$ 18.5	0.07 $\pm$ 0.01	1.56 $\pm$ 0.59	0.03 $\pm$ 0	9.35 $\pm$ 0.45	5.47 $\pm$ 0.83
Aug	29.7 $\pm$ 0.6	34.2 $\pm$ 0.3	5.91 $\pm$ 0.42	8.1 $\pm$ 0	26.8 $\pm$ 0	0.03 $\pm$ 0	1.28 $\pm$ 0	0.01 $\pm$ 0	11.20 $\pm$ 0	2.66 $\pm$ 0
Sep	29.2 $\pm$ 0.7	34.6 $\pm$ 0.3	6.24 $\pm$ 0.22	8.1 $\pm$ 0	19.2 $\pm$ 10.1	0.01 $\pm$ 0.01	1.47 $\pm$ 0.41	0.01 $\pm$ 0.01	13.55 $\pm$ 1.55	3.40 $\pm$ 0.19
Oct	31.2 $\pm$ 0.4	30.7 $\pm$ 1.4	5.56 $\pm$ 0.21	7.9 $\pm$ 0.1	36.9 $\pm$ 16.0	0.02 $\pm$ 0	0.76 $\pm$ 0.09	0.01 $\pm$ 0.01	12.60 $\pm$ 2.60	1.10 $\pm$ 0.49
Nov	27.4 $\pm$ 0.6	27.0 $\pm$ 0.3	6.51 $\pm$ 0.11	8.1 $\pm$ 0	29.0 $\pm$ 13.3	0.02 $\pm$ 0	0.98 $\pm$ 0.08	0.05 $\pm$ 0.03	16.15 $\pm$ 1.75	1.06 $\pm$ 0.27
Dec	26.2 $\pm$ 0	32.7 $\pm$ 0.3	5.19 $\pm$ 0.07	8.2 $\pm$ 0.2	44.7 $\pm$ 2.4	0.02 $\pm$ 0	0.51 $\pm$ 0.08	0.03 $\pm$ 0.02	5.40 $\pm$ 1.20	1.97 $\pm$ 0.73
Jan 1989	26.9 $\pm$ 0.1	34.0 $\pm$ 0.1	5.89 $\pm$ 0.12	8.2 $\pm$ 0	14.9 $\pm$ 2.4	0.01 $\pm$ 0.01	0.47 $\pm$ 0.07	0.03 $\pm$ 0.01	4.15 $\pm$ 1.45	2.12 $\pm$ 0.84
Feb	30.5 $\pm$ 0.1	34.6 $\pm$ 0.1	5.30 $\pm$ 0.51	8.2 $\pm$ 0	18.6 $\pm$ 2.3	0.01 $\pm$ 0.01	0.37 $\pm$ 0.05	0	6.30 $\pm$ 0.60	2.04 $\pm$ 0.71
Mar	29.9 $\pm$ 0.1	34.7 $\pm$ 0.1	5.67 $\pm$ 0.20	8.1 $\pm$ 0	22.4 $\pm$ 0	0.03 $\pm$ 0	0.47 $\pm$ 0	0.02 $\pm$ 0	4.30 $\pm$ 0	3.88 $\pm$ 0
Apr	29.6 $\pm$ 0.1	34.7 $\pm$ 0	5.15 $\pm$ 0.60	8.1 $\pm$ 0	29.1 $\pm$ 5.0	0.03 $\pm$ 0	0.39 $\pm$ 0.02	0.07 $\pm$ 0.01	2.50 $\pm$ 0.30	3.22 $\pm$ 1.13
May	30.6 $\pm$ 0.2	34.5 $\pm$ 0.2	4.96 $\pm$ 0.02	8.0 $\pm$ 0.1	17.0 $\pm$ 2.5	0.01 $\pm$ 0	0.60 $\pm$ 0.07	0.02 $\pm$ 0.02	1.95 $\pm$ 0.35	6.04 $\pm$ 0.83
Jun	30.9 $\pm$ 0.6	35.1 $\pm$ 0.1	4.19 $\pm$ 0.26	8.2 $\pm$ 0.2	21.3 $\pm$ 9.1	0.02 $\pm$ 0	0.51 $\pm$ 0.07	0.05 $\pm$ 0	1.90 $\pm$ 0.10	5.70 $\pm$ 1.81
Jul	28.2 $\pm$ 0.3	33.7 $\pm$ 0.1	5.49 $\pm$ 0.25	8.2 $\pm$ 0	18.0 $\pm$ 3.3	0.03 $\pm$ 0	0.98 $\pm$ 0.05	0.01 $\pm$ 0.01	4.70 $\pm$ 0.80	2.85 $\pm$ 1.31
Aug	28.9 $\pm$ 0.1	34.1 $\pm$ 0.1	5.72 $\pm$ 0.54	8.0 $\pm$ 0	24.4 $\pm$ 0	0.02 $\pm$ 0	1.03 $\pm$ 0	0	5.30 $\pm$ 0	6.17 $\pm$ 0
Sep	28.9 $\pm$ 0.5	34.5 $\pm$ 0.2	5.28 $\pm$ 0.34	8.1 $\pm$ 0	17.8 $\pm$ 0	0.03 $\pm$ 0	0.59 $\pm$ 0	0	3.50 $\pm$ 0	1.39 $\pm$ 0
Oct	31.3 $\pm$ 0.4	32.7 $\pm$ 0.3	5.91 $\pm$ 0.27	8.0 $\pm$ 0.1	23.3 $\pm$ 0	0.04 $\pm$ 0	1.05 $\pm$ 0	0.01 $\pm$ 0	7.90 $\pm$ 0	3.32 $\pm$ 0
Nov	27.4 $\pm$ 0.1	25.2 $\pm$ 0.4	5.00 $\pm$ 1.63	7.9 $\pm$ 0.1	36.0 $\pm$ 9.5	0.03 $\pm$ 0	1.29 $\pm$ 0.14	0.07 $\pm$ 0.01	13.45 $\pm$ 2.65	1.20 $\pm$ 0.68
Dec	25.9 $\pm$ 0.1	32.7 $\pm$ 0.3	5.45 $\pm$ 0.32	8.0 $\pm$ 0.1	19.7 $\pm$ 3.7	0.01 $\pm$ 0.01	0.45 $\pm$ 0.06	0.02 $\pm$ 0	6.35 $\pm$ 0.95	1.70 $\pm$ 0.22
Jan 1990	27.2 $\pm$ 0.4	33.7 $\pm$ 0.1	5.26 $\pm$ 0.32	8.2 $\pm$ 0	20.1 $\pm$ 0.2	0.01 $\pm$ 0.01	0.52 $\pm$ 0.07	0.01 $\pm$ 0.01	3.50 $\pm$ 0.20	1.99 $\pm$ 0.21
Feb	29.2 $\pm$ 0.3	33.9 $\pm$ 0.2	5.41 $\pm$ 0.17	8.1 $\pm$ 0	15.8 $\pm$ 1.1	0.01 $\pm$ 0.01	0.52 $\pm$ 0.04	0.02 $\pm$ 0.02	3.30 $\pm$ 0.34	3.25 $\pm$ 0.03
Mar	29.9 $\pm$ 0.6	34.1 $\pm$ 0.1	5.07 $\pm$ 0.45	8.2 $\pm$ 0.1	33.8 $\pm$ 12.6	0.02 $\pm$ 0	0.53 $\pm$ 0.11	0.05 $\pm$ 0.01	5.10 $\pm$ 0.30	2.56 $\pm$ 0.26

Fig. 2. Variations in head loss at the MAPS forebay during 1986–1990 when 11 pumps were operational (dotted line represents design limit).

Head loss

Head loss caused by fouling-induced flow blockage inside the tunnel showed a gradual increase from 1986 to 1987 (Fig. 2). The maximum head loss recorded was 3.44 m on 31 August 1987 and sudden decrease was observed on 18 April 1988. The head loss readings remained within 2.70 m from 30 May 1988 to 12 March 1990.

Diving inspections

Biomass values of fouling debris collected by divers from inside the tunnel system show a maximum value of 211 kg/m² inside the forebay shaft at a depth of 22.5 m (Table 2). The minimum value observed was 35 kg/m² at a depth of 5 m in the forebay shaft. The average biomass values for the intake and forebay shaft were 70 and 105 kg/m², respectively. Two samples collected from the horizontal conduit gave an average biomass value of 66 kg/m². The total biomass of fouling debris in the entire tunnel system was also estimated based on the biomass levels in different sections. This was found to be 578 tonnes (wet weight), of which the contribution of green mussel alone was 411 tonnes (Rajagopal *et al.*, 1991a).

Volume transport

The volume of seawater transported through the intake tunnel during the period January 1988 to January 1990 (Table 3), ranged from 5.16×10^5 m³/day (January 1988) to 3.66×10^6 m³/day (July 1988). Lower values during January to February 1988 and January to June 1989, indicate shut-down periods of the plant when only a limited number of pumps were operated.

TABLE 2

Fouling Biomass Collected by Divers at the 19 Sampling Points from the Cooling Conduits of Madras Atomic Power Station

Depth (m)	Fouling biomass (kg/m ²)		
	<i>Perna viridis</i>	Other fouling species	Total biomass
Intake - 3	29.76	9.24	39.0
Intake -3	35.76	5.44	41.2
Intake - 9	28.40	7.60	36.0
Intake -18	109.00	20.30	129.3
Intake -18	88.62	17.38	106.0
Forebay - 5	10.21	24.39	34.6
Forebay - 6	51.71	23.89	75.6
Forebay - 6	101.32	40.98	142.3
Forebay - 7.5	37.02	10.08	47.1
Forebay -12	136.31	25.19	161.5
Forebay -22.5	184.92	26.18	211.1
Forebay -36	110.12	22.08	132.2
Forebay -48	75.11	23.59	98.7
Forebay -48	92.17	8.23	100.4
Forebay -49	14.05	27.65	41.7
Forebay -50	81.81	21.49	103.3
Forebay -53	94.71	15.29	110.0
Inside tunnel -8m (49m)	33.99	24.91	58.9
Inside tunnel -8m (53m)	53.44	19.36	72.8

Chlorine doses

Monthly averages of chlorine added (calculated value) and residual chlorine levels recorded in the forebay are given in Table 3. The difference between these two data gives a measure of the chlorine demand of the cooling water. Higher doses were administered in the months January and February 1988 which gave a total residual of 1.4 mg/litre or more at the forebay. From May 1988 onwards continuous low-level chlorination was resorted to, in order to give a residual level of 0.2 mg/litre or less, and this was maintained for the rest of the period. However, during the months of May and June 1989, slightly higher doses (average 1.6 mg/litre) were used.

Fouling debris removal from the tunnel

Quantitative data on fouling debris collected on TWS shows a higher rate of removal during the three month period following high-level chlorination (Fig. 3). A maximum of 45.4 tonnes was collected in February 1988. During the period of study, total number of taxa collected on the TWS was found to be 98, of which 61 were Mollusca (Table 4). However, TWS collection was mostly dominated by the green mussel, *P. viridis*, as expected. Monthly variations in relative abundance of green mussels also clearly indicated its dominance over the other species on the TWS collection (Fig. 4). A total biomass of about 187 tonnes of fouling debris was collected from TWS during February 1988 to

TABLE 3

Seawater Volume Transport, Injected Chlorine Dose and Measured Levels of Residual Chlorine in the Forebay During January 1988 to January 1990 (Monthly Mean $\pm$ SD)

<i>Months</i>	<i>Injected chlorine dose (mg/litre)</i>	<i>Residual chlorine at forebay (mg/litre)</i>	<i>Seawater volume transport (m³/day) $\times 10^3$</i>
*Jan 1988	3.37 $\pm$ 0.92	2.09 $\pm$ 0.63	516.4
*Feb	2.55 $\pm$ 0.67	1.38 $\pm$ 0.40	1651.4
*Mar	1.11 $\pm$ 0.28	0.51 $\pm$ 0.19	2567.7
Apr	0.85 $\pm$ 0.30	0.32 $\pm$ 0.18	3353.7
May	0.40 $\pm$ 0.11	0.17 $\pm$ 0.05	3382.4
Jun	0.26 $\pm$ 0.09	0.09 $\pm$ 0.01	3480.3
Jul	0.24 $\pm$ 0.10	0.05 $\pm$ 0.01	3661.5
Aug	0.29 $\pm$ 0.14	0.00 $\pm$ 0.08	3295.9
Sept	0.34 $\pm$ 0.08	0.13 $\pm$ 0.03	2298.5
Oct	0.43 $\pm$ 0.17	0.18 $\pm$ 0.10	2094.2
Nov	0.36 $\pm$ 0.11	0.16 $\pm$ 0.05	2547.7
Dec	0.43 $\pm$ 0.22	0.21 $\pm$ 0.07	2496.1
Jan 1989	0.95 $\pm$ 0.39	0.38 $\pm$ 0.21	1446.7
Feb	0.71 $\pm$ 0.45	0.30 $\pm$ 0.19	1414.6
Mar	0.61 $\pm$ 0.34	0.24 $\pm$ 0.15	1252.6
Apr	0.78 $\pm$ 0.30	0.43 $\pm$ 0.23	841.9
May	1.57 $\pm$ 0.79	0.63 $\pm$ 0.37	1049.7
Jun	1.69 $\pm$ 1.03	0.84 $\pm$ 0.69	1038.7
Jul	0.23 $\pm$ 0.18	0.06 $\pm$ 0.01	3369.6
Aug	0.65 $\pm$ 0.27	0.29 $\pm$ 0.12	3407.8
Sept	0.23 $\pm$ 0.09	0.02 $\pm$ 0.01	3483.3
Oct	0.36 $\pm$ 0.15	0.16 $\pm$ 0.04	3298.3
Nov	0.42 $\pm$ 0.29	0.22 $\pm$ 0.08	3184.3
Dec	0.37 $\pm$ 0.18	0.13 $\pm$ 0.07	3145.3
Jan 1990	0.27 $\pm$ 0.07	0.08 $\pm$ 0.02	2766.2

*Data obtained from APS log book.

January 1990 (Table 5). Of this, green mussels accounted for 164 tonnes (88%), followed by barnacles (2.7%) and snails (2.4%).

The percentage of live mussels (Fig. 5) in the fouling debris was relatively low during the months of February (9.3%), March (1.2%) and April 1988 (0.8%). Thereafter, the values increased to about 50% indicating large-scale removal of live mussels from the intake tunnel. However, most of these live mussels were smaller in size (1 to 3 cm shell length), compared to the dead and decaying ones. A similar pattern was also noticed in 1989.

The size-frequency distribution of mussels collected on the TWS during the period February 1988 to January 1990 (Fig. 6) shows that, in the initial months following high-level chlorination, the mussels which were removed from the tunnel were comparatively larger in size, i.e. 7 cm or more. During the period February to April 1988, the modal size group shifted from 7–9 cm to 10–11 cm and 11–12 cm, indicating a progressive delay in the expulsion of mussels as their size increased. However, in May 1988, young green mussels

Fig. 3. Biomass of fouling debris collected on travelling water screens at forebay during February 1988 to January 1990.

(0–3 cm) started appearing in the collection. Their appearance is correlated with the breeding pattern of green mussels in the adjoining coastal waters (Rajagopal *et al.*, 1991b). In the following months, the relative frequency of the smaller green mussels increased in the collection with an accompanying reduction in the number of larger mussels. An appearance of young mussels was also recorded during October 1988, May–June 1989 and October 1989, which again coincided with the observed breeding cycle of the green mussels at Kalpakkam.

Growth rate

Experiments on the growth rate of mussels in the Kalpakkam coastal waters (Fig. 7) showed that the mussels achieved a shell length of 13.1 ± 0.5 mm in 30 days (30 April 1988) and 98.1 ± 0.7 in 370 days (5 April 1989).

DISCUSSION

Chlorination is commonly used to prevent settlement of fouling organisms, particularly mussels, in cooling conduits of power stations (Yamazaki, 1965; Whitehouse, 1978; Whitehouse *et al.*, 1985). Mussel control using chlorination is well documented in the literature. Turner *et al.* (1948) and Anderson & Richards (1966) observed that intermittent chlorination failed to prevent mussel settlement and growth in power plants. James (1967) also reported the ineffectiveness of the intermittent chlorination for controlling fouling in Carmarthen Bay power station. Holmes (1970a) suggested that mussels settled between intermittent chlorine injections were able to resist the subsequent exposures to chlorine. In intermittent chlorinated waters, recuperation of mussels is possible because during the

TABLE 4
List of Fouling Organisms Observed in the Cooling System of the Madras Atomic Power Station

Coelenterata	
Campanulariidae	<i>Obelia bicuspidata</i> Clarke
Bougainvilliidae	<i>Bimeria vestita</i> Wright
Sertulariidae	<i>Sertularia</i> sp.
Sagartiidae	<i>Sagartia</i> sp.
Porifera	
Callyspongiidae	<i>Callyspongia diffusa</i> (Ridley)
Tedaniidae	<i>Tedania anhelans</i> (Lieberkuhn)
Mycalidae	<i>Mycale mytilorum</i> Annandale
Ectoprocta	
Bicellariellidae	<i>Bugula</i> sp.
Electridae	<i>Electra</i> sp. <i>Acanthodesia</i> sp. <i>Alderina arabianensis</i> Menon & Nair
Membraniporidae	<i>Membranipora</i> sp.
Annelida	
Nereidae	<i>Perinereis</i> sp. <i>Platynereis</i> sp. <i>Pseudonereis</i> sp. <i>Nereis</i> sp.
Sabellidae	<i>Dasychone</i> sp. <i>Sabellestarte</i> sp.
Serpulidae	<i>Ficopomatus</i> sp. <i>Hydroides elegans</i> (Haswell) <i>Serpula vermicularis</i> Linnaeus
Arthropoda	
Balanidae	<i>Megabalanus tintinnabulum</i> (Linnaeus) <i>Balanus amphitrite</i> Darwin <i>Balanus amaryllus</i> var <i>euamaryllis</i> Broch <i>Balanus reticulatus</i> Darwin

TABLE 4—contd.

Mollusca

Patellidae

Cellana radiata radiata Born

Trochidae

Euchelus asper Gmelin

Muricidae

Ergalatax contracta (Reeve)*Thais bufo* Lamarck*Thais blanfordi* (Melvill)*Thais rugosa* (Born)*Thais tissoti* (Petit)

Ranellidae

Lampusia pileare (Linnaeus)*Cymatium cingulatum* Lamarck*Gyrineum natator* (Roeding)

Architectonicidae

Architectonica perspectiva Linnaeus

Turritellidae

Turritella acutangula Linnaeus*Turritella attenuata* Reeve

Nassariidae

Bullia vittata (Linnaeus)*Bullia melanoides* Deshayes

Littorinidae

Littorina (*Littoraria*) *undulata* (Gray)*Littorina* (*Littoringsis*) *scabra scabra* (Linnaeus)

Potamididae

Cerithidea (*Cerithideopsilla*) *cingulata* (Gmelin)*Cerithidea fluviatilis* Potiez & Michand*Telescopium telescopium* (Linnaeus)

Cypraeidae

Cypraea gracilis Gaskoin

Olividae

Olivancillaria gibbosa (Born)

Dorididae

Discodoris concinna Alder & Hancock

Dendrodorididae

Doriopsilla miniata Alder & Hancock

Tergipedidae

Caloria militaris Alter & Hancock

Arcidae

Anadara rhombea Born*Anadara granosa* Linnaeus*Arca avellana* Lamarck*Arca fusca* Bruguière*Arca symmetrica* Reeve*Arca gubbernaculum* Reeve

TABLE 4—contd.

Mollusca—	contd.
Cardiidae	<i>Vepricardium coronatum</i> (Spengler)
Donacidae	<i>Donax scortum</i> Linnaeus <i>Donax cuneatus</i> (Linnaeus) <i>Donax aperittus</i> Melvill
Veneridae	<i>Meretrix casta</i> Chemnitz <i>Meretrix meretrix</i> (Linnaeus) <i>Timoclea arakana</i> (G & H Newill) <i>Irus exoticus</i> (Hanley) <i>Paphia textile</i> (Gmelin) <i>Paphia gallus</i> (Gmelin)
Tellinidae	<i>Tellina angulata</i> (Gmelin)
Carditidae	<i>Beguinia variegata</i> (Bruguère)
Ostreidae	<i>Crassostrea madrasensis</i> Preston <i>Saccostrea cucullata</i> Born
Pteriidae	<i>Pinctada anomioides</i> Reeve <i>Pinctada chemnitzii</i> (Philippi) <i>Pinctada margaritifera</i> Linnaeus
Chamidae	<i>Chama reflexa</i> Reeve <i>Chama lazarus</i> Linnaeus <i>Chama fragrum</i> Reeve <i>Pseudochama cristella</i> Lamarck
Mytilidae	<i>Perna viridis</i> (Linnaeus) <i>Perna indica</i> Kuriakose & Nair <i>Modiolus striatulus</i> Hanley <i>Modiolus modiolus</i> Linnaeus <i>Modiolus undulata</i> Dunker <i>Modiolus metcalfei</i> Hanley <i>Modiolus perfragilis</i> Dunker <i>Modiolus philippinarum</i> (Hanley)
Echinodermata	
Ophiuridae	<i>Ophiothrix exigua</i> Lyman
Chordata	
Urochordata	
Didemnidae	<i>Didemnum psammathodes</i> Sluiter <i>Diplosoma macdonaldi</i> Herdman <i>Lissoclinum fragile</i> Van Name

TABLE 4—*contd.*

Chordata— <i>contd.</i>	
Urochordata	
Polyclinidae	<i>Aplidium multiplicatum</i> Sluiter
Styelidae	<i>Symplegma brakenhielmi</i> Michaelson <i>Symplegma viride</i> Herdman <i>Styela bicolor</i> Sluiter <i>Botrylloides magnicoecum</i> Hertmeyer <i>Polycarpa</i> sp.
Asciidiidae	<i>Ascidia zara</i> Oka <i>Ascidella aspersa</i> Müller

* Entrained organisms such as jelly fishes and fishes are not included in the list.

TABLE 5

Seasonal Variation of Relative Abundance of Different Fouling Debris on TWS in the Forebay During February 1988 to January 1990 (Wet Weight in Kilograms)

Months	<i>Perna viridis</i>	Other fouling species	Total biomass
Feb 1988	44114	1250	45364
Mar	42005	1282	43287
Apr	35515	1088	36603
May	9577	3786	13363
Jun	7577	3162	10739
Jul	6256	3460	9717
Aug	7066	2331	9397
Sept	309	104	413
Oct	2165	2356	4521
Nov	1796	1193	2989
Dec	372	108	480
Jan 1989	220	53	273
Feb	238	52	290
Mar	309	260	569
Apr	205	33	238
May	432	131	563
Jun	883	162	1045
Jul	968	293	1261
Aug	689	258	947
Sept	1923	594	2517
Oct	789	239	1028
Nov	324	98	422
Dec	290	65	355
Jan 1990	229	40	269
Total	164251	22397	186648
Percentage	88.0	12.0	100.0

Fig. 4. Monthly variations of relative percentage (number and weight) of green mussel, *Perna viridis*, collected on travelling water screens at the forebay during February 1988 to January 1990.

breaks in chlorination they can actively feed and produce byssus threads (Rajagopal *et al.*, 1991b, 1994b). In addition, the steady flow conditions inside cooling conduits of power plants facilitates increased food availability (Jenner, 1982) and removal of metabolic wastes (Perkins, 1974; Neitzel *et al.*, 1986). Therefore, mussels can easily compensate for any resource drain caused by short-term chlorination (Coughlan & Whitehouse, 1981; Rajagopal *et al.*, 1991a). The present data on head loss at forebay (Fig. 2) also clearly

Fig. 5. Percentage composition of live and dead *Perna viridis* collected on travelling water screens at the forebay during February 1988 to January 1990.

indicate that the intermittent chlorination has not been effective in checking tunnel fouling at MAPS. Lewis (1985) noted that mussels treated with chlorine residuals of 4.43 mg/litre for 49 h, were capable of making recovery within 30 min of exposure to ambient seawater. Jensen (1982) found that the mussels failed to recover after a 24 h exposure to a chlorine residual of 8 to 40 mg/litre. It is reasonable to conclude that at high chlorine residuals (eg. 40 mg/litre), denaturation of cell membranes could lead to lethal effects, particularly in the gills (Opresko, 1980), but at low residuals only other physiological activities of mussels are affected (Khalanski & Bordet, 1980).

Studies on the biofouling at Kalpakkam during the pre-operational phase of the power plant had predicted that barnacles, *Balanus* sp., would be the dominant fouling organism in the cooling system (Godwin, 1980; Karande *et al.*, 1983). It was also pointed out that the average monthly biomass build-up at Kalpakkam coastal waters would be about 4 kg/m² with a possible yearly maximum of about 80 kg/m² (Karande *et al.*, 1983). However the present study clearly demonstrates that tunnel fouling is actually dominated by the green mussel, *P. viridis*. The earlier studies were conducted by exposing test panels near the intake area and drawing conclusions based on the results thus obtained. This example points to the potential dangers involved in extrapolating test panel data to predict the extent and type of fouling in specialised environments such as cooling conduits of power stations. The present study also shows a maximum biomass value of 211 kg/m² in the forebay shaft. The comparison of the biomass values at Kalpakkam with those reported in the literature shows that biomass build-up in Kalpakkam is probably one of the highest ever reported. The nearest value reported in the literature is 64 kg/m² from the water intake tunnels of a power plant at Lynn, Massachusetts (Woods Hole Oceanographic Institution, 1952). Such very high biomass accumulations at MAPS are possible because of the extremely dense settlement of bivalves, especially *P. viridis*. In the

Fig. 6. Size-frequency distribution of *Perna viridis* collected on travelling water screens at the forebay during February 1988 to January 1990.

process of colonization of specialized environments such as seawater intake tunnels (existing flow rates, darkness and increased food availability), mussels have a competitive edge over most of the other fouling groups, and therefore mussel domination in such environments is likely at other similar localities also. In the present study, fouling debris removal data also confirmed the dominance of green mussels over the other fouling species in the cooling conduits of MAPS (Table 5).

Following high-level chlorination, fouling debris started to appear on the TWS at the forebay. During the period, February to April 1988, fouling debris dominated by *P. viridis* (>98%) of large size (8 to 12 cm shell length) continued to get collected on the TWS.

Fig. 7. Growth rate (mean $\pm$ SE, $n=30$) of *Perna viridis* in the Kalpakkam coastal waters from April 1988 to April 1989.

Most of the mussel shells contained remains of fresh tissue, suggesting a very recent demise resulting from the application of high-level chlorination. Nevertheless, mussels inside the tunnel had a layered growth pattern (as evidenced by visual observations by ROV) which precludes direct byssal contact with the primary substratum (culvert wall) for many mussels. Seed (1976) reported that mussels attached to solid substrates are relatively secure but, as the mussel bed develops, most of the mussels lose contact with the substrate and form a surface layer with feeble attachment to one another by long weak byssus threads. Thus it appears that in the early stages of fouling, mussels would have good byssal contact with the culvert wall, however, as the fouling develops and forms a thicker layer, it could become increasingly unstable and vulnerable to erosion, as suggested by Lewis (1961), Holmes (1970a) and Jenner (1983). This explains why progressive delay in the duration of expulsion of already established mussel population from the cooling conduits of MAPS. The removal of fouling debris from the intake system not only depends on the amount of chlorine injected during the chlorination regime but also on volume transport (in other words water velocity) of seawater (Fig. 8). The fate of fouling organisms (especially bivalves) within a cooling conduit is partially dependent on the flow rates within the system (Neitzel *et al.*, 1984; Nair, 1990). Flow velocities of less than 1.2 m/sec are known to allow mussel larvae to settle (Holmes, 1967). Once established, mussel communities are known to withstand velocities ranging from 1.5 to 2.5 m/sec (Collins, 1964; Burton & Liden, 1978). However, flow velocities below 0.1 m/sec may not provide adequate food and oxygen or facilitate removal of metabolic wastes fast enough to allow dense mussel growth (Jenner, 1980; Henager *et al.*, 1985; Venugopalan & Nair, 1990). It is also known that if velocities are too fast to allow settlement, bivalves will not become established (Lewis, 1964). In the present study, the observed maximum (2517 kg) and minimum (238 kg) arrival of fouling debris on TWS for the year 1989 (Fig. 8) significantly correlated with the amount of seawater volume transported through the tunnel (Spearman rank correlation test, $p < 0.001$). It is obvious that the shearing force created by the moving water helps removal of attached fouling biomass which has already loosened by application of chlorination. However, the data for 1988 did not show any

Fig. 8. Relationship between volume transport of seawater and travelling water screen debris collection at the forebay during 1989.

relation between volume transport and fouling debris on TWS. This is possibly due to the combined effects of already established fouling communities inside the MAPS submarine tunnel and adopted higher doses of chlorine residuals.

Young green mussels (0 to 3 cm shell length) started appearing on TWS during May to July 1988, October 1988, May to June 1989 and October 1989, which corresponds with the breeding season of *P. viridis* in Kalpakkam coastal waters (Rajagopal, 1991). Most of these young mussels (>50%) were alive when collected on the TWS (Fig. 5), which apparently shows that continuous low-level chlorination helps to flush out juvenile mussels, before they are able to secure attachment on the tunnel walls. It is not clear whether the green mussels were actively migrating out of the tunnel as suggested by James (1967) or whether they were carried away by the flowing water as their byssal attachment was weakened because of chlorination (Holmes, 1970b). It is unlikely that continuous low-level chlorination completely eliminated settlement of young mussels. Size-frequency distribution of *P. viridis* collected on the TWS also shows a significant progressive increase in shell length, subsequent to the breeding seasons (Fig. 6). Jenner (1983) reported that there was no evidence that continuous chlorination had reduced mussel settlement in cooling conduits. He found, using side-stream monitors, that during periods of continuous chlorination at a mean residual of 0.2 mg/litre (0.1–0.25 mg/litre), chlorine had no effect on the blue mussel, *Mytilus edulis* (L.), settlement at Maasvlakte power station, near Rotterdam. Khalanski & Bordet (1980) observed that at a chlorine level between 0.2 and 0.5 mg/litre, settlement is delayed for 30% of the mussel larvae. Thus, it seems possible that a combined effect of general weakening of the byssus attachment (Holmes, 1970a) and high flow rates inside cooling conduits, is probably responsible for such mass exodus of live mussels. It is obvious from the head loss data that MAPS intake tunnel continued to become increasingly fouled when continuous low-level chlorination was employed (Fig. 2). Given the very real difficulties of actually inspecting power station cooling water

culverts, such head loss data is one of the few pragmatic means of monitoring the progress of fouling. Side stream fouling monitors, as described by Jenner (1985), can provide additional helpful data. In tandem, the two methods will tend to provide information on the onset, extent and character of fouling inside the cooling water culverts, together with an assessment of the control methods employed.

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