SUBTIDAL AND INTERTIDAL MARINE FOULING ON ARTIFICIAL SUBSTRATA IN NORTHERN PUGET SOUND, WASHINGTON[1]

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ABSTRACT

The design and siting of power plant cooling systems requires detailed information concerning the fouling tendencies of specific organisms on specific construction materials. This study, conducted in the vicinity of Kiket Island, northern Puget Sound, Wash., attempts to provide some of this information.

The sessile community characteristics of five materials exposed at three depths and two locations in the subtidal zone, and of one material in the intertidal zone are described. The degree of biofouling was least for copper-nickel alloy and progressively greater for Plexiglas, wood, steel, and concrete. Media decay and biological accumulation was greatest at the near-surface level, decreasing in intensity with increasing depth. The maximum rate of colonization occurred during the late spring (April-June) and early fall (mid-August-October). The present study, an analysis of biofouling, indicates that if the proposed power plant were to be built at Kiket Island, its cooling system intake should be sited in water deeper than 6 m and should have a safe and adequate fouling control scheme.

The settlement of entrained fouling organisms seriously affects the proper functioning of industrial cooling systems (Dobson 1946; Beauchamp 1966; Holmes 1970). Thus, the design of a cooling system requires detailed information concerning the fouling tendencies of specific organisms on specific construction materials. The present study — conducted in the vicinity of Kiket Island, northern Puget Sound, Wash.—attempts to provide some of this information. At the time, the study area was the proposed site for a 1,000 MW nuclear power plant with a once-through cooling system.

The study analyzed the fouling resistances of several common construction materials both in the subtidal and in the intertidal zones. Colonization in the subtidal zone was examined from April to November 1972, while colonization in the intertidal zone was examined from December 1971 to September 1972. Short-term (series I) and long-term (series II) exposures of test materials provided information about the rate of fouling accumulations and progressive community change. The study also determined the seasonal and vertical distribution of the dominant fouling organisms endemic to the Kiket Island area. These exposures also allowed a determination of the periods of maximum colonization by fouling organisms.

MATERIALS AND METHODS

Subtidal Fouling

Two test sites for the study of subtidal fouling were established offshore from Kiket and Skagit islands (Figure 1), in water of a mean depth of 18 m. At each test site five construction materials were tested for their resistances to fouling. The materials that were tested included a 90% copper-10% nickel alloy, steel, Plexiglas[4] (an acrylic plastic), white pine wood, and concrete. The materials were cut into 10 cm × 10 cm squares—54 squares each of steel, Plexiglas, and wood; 18 squares each of copper-nickel alloy and concrete. The squares or "plates" had two 12.7-mm holes drilled into opposite corners of the plate. Rope was threaded through the holes and the plates were then separated into 18 "test panels"—each panel having three plates of steel, Plexiglas, and wood, and one plate of copper-nickel alloy and concrete. Within each panel there was a random distribution of plates.

The test panels were suspended in the water at mean depths of 1, 6.1, and 15.3 m below the sur-

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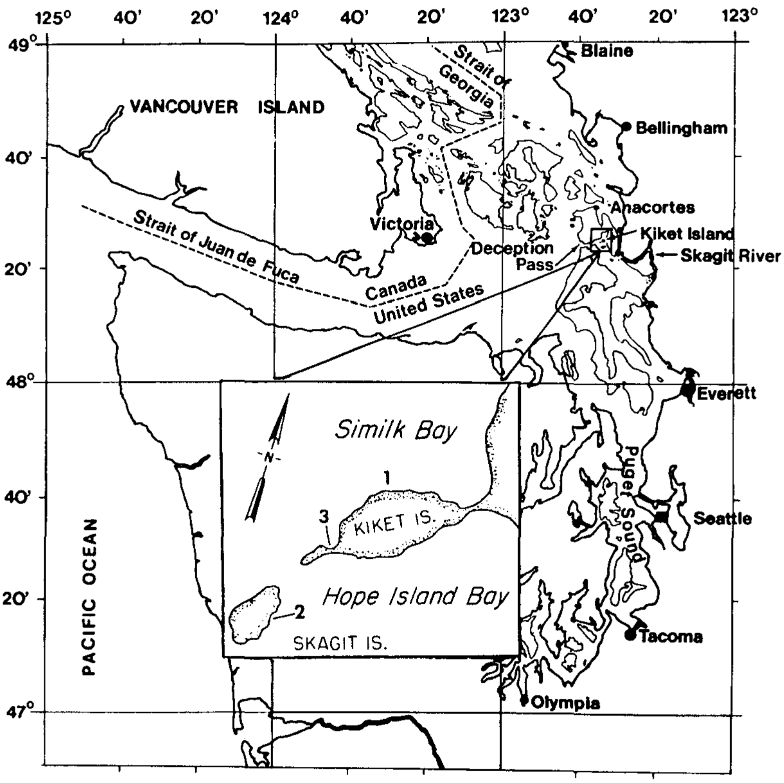

FIGURE 1. — Map of western Washington, with the study areas shown in inset: 1) Kiket Island subtidal site; 2) Skagit Island subtidal site; and 3) intertidal site.

face. The 1-m depth test panels were suspended from a steel surface float. The 6.1- and 15.3-m depth test panels were suspended between a concrete bottom anchor and a steel float moored just below the extreme low water level. At both test sites three panels were deployed at each depth (Figure 2).

Series I test panels were exposed for periods of 41 and 79 days offshore from Skagit Island and were exposed for 58 and 101 days offshore from Kiket Island. Series II test panels were exposed continuously for a period of 8 mo (16 April-29 November 1972) at both locations.

The standard analytical procedure for series I plates involved identification of the organisms, estimation of the percent of plate coverage, and, if possible, a measurement of the size of the organisms. A central square of each plate, measuring 7 cm × 7 cm, was used for analysis. The fouling organisms on each 49-cm² central area were scraped onto preweighed filter paper, dried at approximately 100°C for 24 h, and then weighed to 0.01 g. Monthly qualitative observations of series II plates, anchors, lines, and floats were made using scuba.

Intertidal Fouling

An examination was made of the settling rate of intertidal fouling organisms on concrete slabs. The concrete slabs measured 38 cm wide by 76 cm long by 15 cm deep. The slabs were uniform in texture, composition, surface configuration, stability, and resistance to wave action. They were anchored to the beach with steel reinforcing bars imbedded in the concrete. The long dimension was parallel to the water and the top surface was placed horizontal to the plane of the water. The slabs were positioned at the +0.6-, 0-, −0.6-, and −1.2-m water levels relative to mean sea level. Once each month the density of the fouling organisms was determined from a series of randomly chosen 49-cm² areas on each concrete slab.

RESULTS

Physicochemical Environment

Seasonal water quality data for the Kiket Island area have been described in detail (Stober et al.

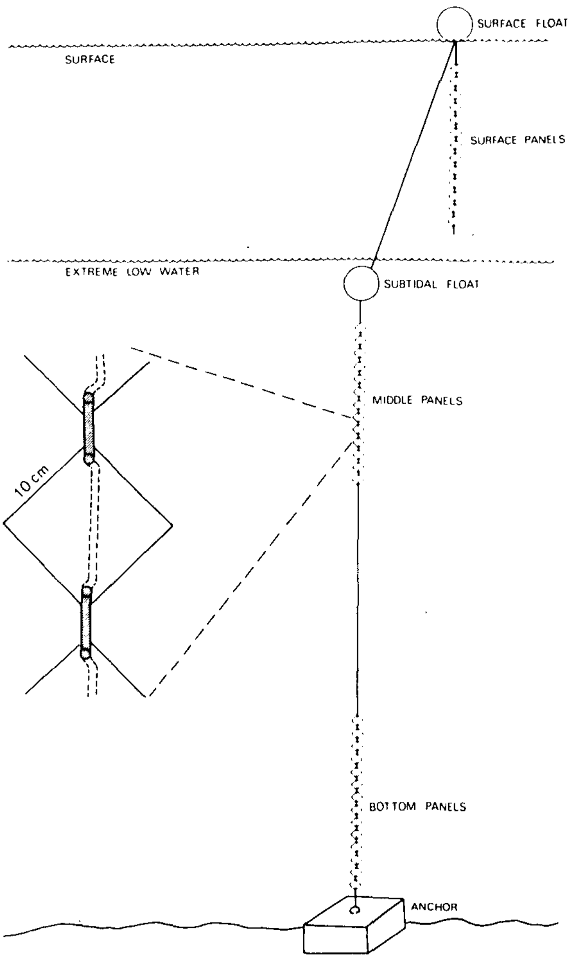

FIGURE 2.—A schematic of the array of subtidal test panels used to measure biofouling with inset showing details of test plate attachment.

1973). Weekly minimum, mean, and maximum temperature and salinity readings are presented in Figure 3. Average weekly temperatures ranged from 6.2°C to 11.8°C. Average weekly salinities ranged from 17.5 to 29.7 g/liter; pH ranged from 7.1 to 8.2; and dissolved oxygen concentrations ranged from 10.5 to 13.3 mg/liter. Lincoln et al. (1970) and Bendiner et al. (1972) have detailed the physical oceanography and vertical stratification of the Kiket Island area. The physicochemical characteristics of North Skagit Bay led Stober et al. (1973) to classify the study area as a well mixed estuary.

Qualitative observations of the study area were made periodically while scuba diving. The bottom in the vicinity of the fouling plates at Kiket Island consisted of soft silt and sediment with a few rock outcroppings. Acorn barnacles, *Balanus crenatus*, densely covered the few rock outcroppings, but were otherwise not present. At a depth of 18 m, light penetration was low and bottom currents appeared to be generally slow. In contrast, the bottom at Skagit Island was virtually free of silt and was predominantly covered with cobble and rock outcroppings. The cobble and rock were densely covered with *B. crenatus*. At 18 m, light penetration was moderate and the bottom currents were consistently more rapid than those at the Kiket Island site.

Fouling Colonization of the Construction Materials

The fouling resistances of the different test materials were compared using the dry weights of organisms collected during periodic sampling. The dry weight data for the 1-m level are shown in Table 1. Weight data of the removable material from the 15.3-m and 6.1-m levels were negligible except for the plates of wood and concrete colonized by *Balanus crenatus* (Table 2).

COPPER-NICKEL ALLOY.—There was no removable material through the first 58 days. The

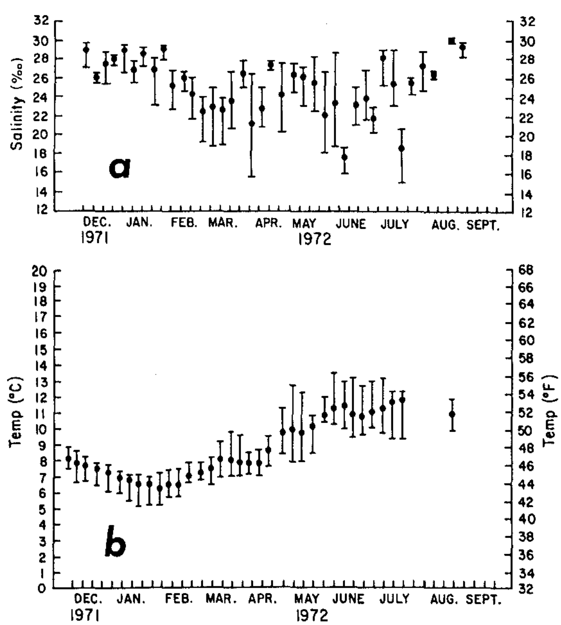

FIGURE 3.—Weekly mean, minimum, and maximum salinity measurements (a) and water temperature (b) recorded in the Kiket Island area (data from Stober et al. 1973).

TABLE 1.—Dry weight in grams of material collected per square centimeter of surface area from five artificial media exposed at the near-surface level for four time periods.

Exposure	Copper-nickel alloy	Steel	Plexiglas	Wood	Concrete
May 26					
41-day exposure	0.00	0.15	0.19	0.13	0.12
June 12					
58-day exposure	0.00	0.26	0.09	0.09	0.07
July 3					
79-day exposure	0.01	0.23	0.08	0.07	0.05
July 25					
101-day exposure	0.01	0.13	0.04	0.05	0.04

TABLE 2.—Density of the barnacle, *Balanus crenatus*, per square centimeter of surface area collected from five artificial media at three depths.

Exposure and depth	Copper-nickel alloy	Steel	Plexiglas	Wood	Concrete
May 26					
41-day exposure					
1 m	0.0	0.0	0.0	0.0	0.0
6.1 m	0.0	0.0	0.0	0.0	0.0
15.3 m	0.0	0.0	0.0	0.0	0.0
June 12					
58-day exposure					
1 m	0.0	0.2	0.1	0.2	2.9
6.1 m	0.0	0.1	0.4	0.3	1.6
15.3 m	0.0	0.0	0.0	0.0	0.4
July 3					
79-day exposure					
1 m	0.0	0.3	0.8	0.4	4.9
6.1 m	0.0	0.0	0.5	4.6	11.3
15.3 m	0.0	0.0	0.0	39	64
July 25					
101-day exposure					
1 m	0.0	0.1	0.2	0.9	2.1
6.1 m	0.0	0.0	0.0	0.0	0.4
15.3 m	0.0	0.0	0.0	0.1	0.0

79-day and the 101-day samples had removable material weighing less than 0.01 g/cm². Removable material consisted primarily of diatoms, with small deposits from flaking of the alloy surface. No mussels, barnacles, or green algae were observed.

STEEL.—After 41 days the dry weight of the removable material was 0.15 g/cm², after 58 days 0.26 g/cm², after 79 days 0.23 g/cm², and after 101 days 0.13 g/cm². A high proportion of the removable material was rust; biological accumulations consisted of diatoms, barnacles, green algae, and mussels. *Balanus crenatus* densities at the 1-m depth ranged from 0.0 on day 41 to 0.3/cm² on day 79. *Balanus* density at the 6.1-m level ranged from 0.0 on day 41 to 0.1/cm² on day 58. No *Balanus* were found at the 15.3-m level.

PLEXIGLAS.—After 41 days the dry weight of the removable material was 0.19 g/cm², after 58 days 0.09 g/cm², after 79 days 0.08 g/cm², and after 101 days 0.04 g/cm². Removable material consisted of diatoms, green algae, and barnacles. Mussels were not observed on the Plexiglas media. The density of *Balanus crenatus* at the 1-m level ranged from 0.0 on day 41 to 0.8/cm² on day 79. At the 6.1-m level *Balanus* densities ranged from 0.0 on day 41 to 0.5/cm² on day 79. No *Balanus* were found at the 15.3-m level.

WOOD.—After 41 days the dry weight of the removable material was 0.13 g/cm², after 58 days 0.09 g/cm², after 79 days 0.07 g/cm², and after 101 days 0.05 g/cm². Removable material consisted primarily of diatoms and barnacles with small amounts of green algae. No mussels were found. The density of *Balanus crenatus* at the 1-m level ranged from 0.0 on day 41 to 0.9/cm² on day 101. *Balanus* density at the 6.1-m level ranged from 0.0 on day 41 to 4.6/cm² on day 79. *Balanus* density at the 15.3-m level ranged from 0.0 on day 41 to 39/cm² on day 79. *Balanus* achieved 100% of plate coverage on day 79 at the 15.3-m level. No wood borers were found at any level.

CONCRETE.—After 41 days the weight of the removable material was 0.12 g/cm², after 58 days 0.07 g/cm², after 79 days 0.05 g/cm², and after 101 days 0.04 g/cm². Removable material consisted of diatoms, barnacles, mussels, and green algae. The density of *Balanus crenatus* at the 1-m level ranged from 0.0 on day 41 to 4.9/cm² on day 79. *Balanus* density at the 6.1-m level ranged from 0.0 on day 41 to 11.3/cm² on day 79. *Balanus* density at the 15.3-m level ranged from 0.0 on day 41 to 64/cm² on day 79. *Balanus* achieved 100% plate coverage on day 79 at the 15.3-m level. Bay mussels, *Mytilus edulis*, achieved a density of 0.4/cm² at the 1-m level — none were found in the deeper water samples.

Intertidal Fouling

The colonization of fouling organisms was observed on concrete test slabs positioned at various levels in the intertidal zone of Kiket Island. The principal algae species colonizing the slabs were *Fucus distichus* and *Ulva lactuca*. The dominant animal species included the acorn barnacle, *Balanus glandula*, and the bay mussel. A detailed examination of the natural vertical and seasonal distribution of the intertidal flora and fauna of Kiket Island is presented by Houghton (1973).

Settlement by barnacles (Figure 4) was the most rapid during late May. Barnacle density peaked in June, but subsequently there was a general decrease in the density—probably due to intraspecific competition for the limited growing area. Barnacle settlement was most successful at the −0.6-m level. There was limited settlement at the —1.2-m level and at the 0.0-m level. No barnacles successfully settled at the +0.6-m level.

Settlement by barnacles at the −1.2-m level appeared to be limited by heavy siltation and diatomaceous growth. The absence of barnacles at the +0.6-m level was principally caused by the extensive exposure of the organisms to sunlight. Successful settlement at the −0.6-m level was the result of a limited exposure to sunlight and of the moderate wave action limiting the silt/diatom buildup.

Settlement by *M. edulis* was predominant at the −0.6-m level, where maximum density was 1.3/cm². *Mytilus edulis* were present in lower densities at the 0.0-m and −1.2-m levels. The same factors affecting settlement by barnacles—exposure to sunlight and the silt-diatom buildup—affected settlement by *M. edulis*. Mussels were observed to attach primarily in the late summer and in the fall (July-October); a few individuals were observed in April and May.

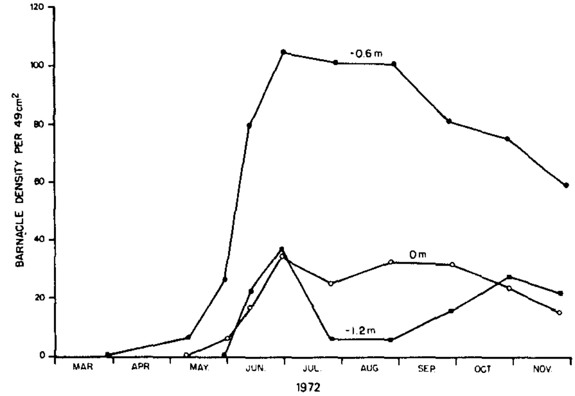

FIGURE 4.—Mean density of *Balanus glandula* attached to concrete substrata exposed in the intertidal zone of Kiket Island (tidal level relative to mean sea level).

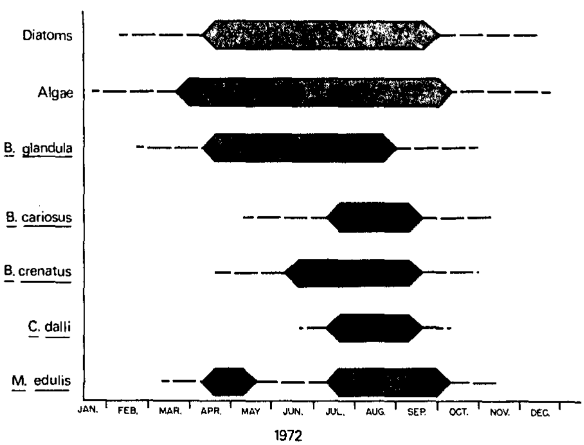

FIGURE 5. — Seasonal distribution of predominant subtidal and intertidal fouling organisms.

Seasonal Distribution of Fouling Organisms

The seasonal distribution of the major sessile fouling organisms found in the Kiket Island area is presented in Figure 5. Conclusions about the distribution of these organisms are based on data collected during a 1½-yr study of intertidal settlement and an 8-mo study of subtidal fouling. Comparable conclusions were reached by DePalma (1966) for Admiralty Inlet.

The first diatoms to appear on the study plates were those of the genus *Melosira*. These diatoms remained dominant throughout the study period. *Navicula* and *Fragilaria,* as well as a large number of unidentified diatoms, also settled on the plates, but were not nearly as abundant as *Melosira.* Although the spores of many diatom species were present all year, settlement occurred predominantly from early spring to midsummer.

Four dominant forms of algae settled on the study plates. *Fucus distichus* and *Ulva lactuca* were dominant in the intertidal zone, while *Ulothrix* sp., *Cladophora* sp., and *Ulva lactuca* were dominant in the subtidal zone. The algae was abundant seasonally—in the spring and summer there was an extensive algal cover on the plates, yet in the fall and winter months the abundance of algae decreased substantially. Many small crustaceans, including copepods, cladocerans, and amphipods, were observed inhabiting the diatoms and algae covering the test plates.

Although barnacles of the genus *Balanus* were present throughout the year, their rate of settlement varied greatly with the different seasons. As a general rule, maximum settlement occurred during the late spring (April-June) and in early fall (mid-August-October). For example, *B. glandula* settled in the intertidal zone from February through November, but the maximum rate of settlement was observed in May and August. However, in the subtidal zone, *B. crenatus* settled from April to November, but with a peak in late July and early August. Others, like *B. cariosus* and *Chthamalus dalli,* settles sporadically from May to November and peaked in August and September.

Settlement by the bay mussel occurred primarily from August to November, although there was some settlement during April and May. It appears that prior settlement by diatoms, algae, and barnacles is necessary for the establishment of a mussel colony. Cleaned test plates were exposed in both the intertidal and the subtidal zones and were compared with plates already having an established community of diatoms, algae, and barnacles. Only on those plates which were already fouled was there any settlement by mussels. Coe (1932) reported the same phenomenon and concluded that the smooth quality of nonfouled surfaces was not suitable for attachment by the byssus of young mussels.

Vertical Distribution in the Subtidal Zone

At both subtidal test sites there was a distinct vertical pattern to the fouling of the test plates. The greatest number of species settled at the near-surface (1-m) level. At that level there were colonial diatoms of the genera *Melosira, Navicula,* and *Fragilaria,* and three species of the acorn barnacle, *Balanus crenatus, B. glandula,* and *B. cariosus*. Subdominant genera included the green algae, *Ulothrix, Ulva,* and *Cladophora*. Small numbers of the bay mussel were also found at the surface level. At the middle depth (6.1 m) the species composition of the fouling organisms changed. Green algae became rare and diatoms were less dense. *Mytilus edulis, B. glandula,* and *B. cariosus* were absent. *Balanus crenatus* increased in density with increasing depth at Skagit Island, but not at the Kiket Island site.

The 15.3-m level was very different from the two upper levels. The plates had no algae or diatoms. *Balanus crenatus* was the dominant species. Consistently higher densities of *B. crenatus* were observed at the Skagit Island test site. The ratio of densities between Skagit and Kiket Island for *B. crenatus* at the 15.3-m level ranged as high as 50 to 1 for the wood and concrete test plates.

DISCUSSION

Marine fouling presents one of the most serious long-term operational problems for power generating stations using saline waters for cooling (Powell 1933; Dobson 1946; Holmes 1970). Fouling accumulations reduce the carrying capacity of cooling system conduits by increasing the frictional resistance and by reducing the pipeline diameter. In addition, marine fouling reduces the heat transfer efficiency of steam condenser systems and promotes severe corrosion of the condenser system components. The accumulation of fouling debris, such as dead shells, adds to the inefficiency by clogging the condenser tubes.

Data are needed by design engineers in order to determine the probable construction requirements for the control of fouling in a power plant cooling system. Because marine fouling varies considerably from one location to another, an onsite determination of the population dynamics of fouling organisms is desirable. Each site should be studied in order to determine: 1) the species composition of sessile organisms colonizing specific construction materials at various subtidal levels, 2) the types of construction materials least likely to be fouled, 3) the seasonal variations in settlement and abundance, and 4) the times of the year when antifouling procedures must be considered. The present study was, in a sense, an attempt to study all these factors, and although the power plant for which the study was intended may never be built, this report should be a useful guide to future studies of power plant siting.

Data for the present study were collected from test plates suspended at various depths in the water. However, caution must be used in extrapolating studies carried out with these small static test plates. Graham and Gay (1945) reported that plates, 9.8 cm × 9.8 cm, were found to give results just as reliable as larger ones. Holmes (pers. commun.), however, considers that "edge effects and top-to-bottom gradients could be very important in biassing results from such small panels." Although no effort was made in the present study to determine the reliability of the small plates, a 3-cm border zone surrounding the 49-cm^2 examination area was considered sufficient to eliminate any edge effect. There was consistently less than 10% variation in the dry weights of the removable material and in the density of barnacles taken from different plates of the same media at the same water level.

One must also recognize that data collected from static test panels can only give a limited indication of the growth rate of fouling organisms in a continuous-flow cooling system (Dobson 1946). Fouling organisms naturally dependent upon water currents to supply food, may have their growth rates enhanced by the greater water velocities of a continuous-flow cooling system (Dobson 1946; Benson et al.[5]). Mawatari[6] observed, however, that test panels exposed in current velocities of 4 to 7 m/s remained totally free of fouling organisms. Efforts to reduce the influence of static plates have been made by several authors (Smith 1946; Doochin and Smith 1951; Wood 1955), but these efforts have produced conflicting results.

Several additional factors should be mentioned which influence both the growth rate and the species composition of sessile organisms colonizing test plates. The larvae of barnacles and many other fouling organisms have been found to be negatively phototrophic when they attach to a surface. Therefore, these organisms prefer to attach to shaded or dark surfaces (Visscher and Luce 1928; Thorson 1964). Also, surface texture has been shown to affect the rate of attachment of settling larvae (Crisp and Ryland 1960; Pomerat and Weiss[7]). In general, porous and rough surfaces have the greatest fouling accumulation.

All of these factors influenced the results obtained by the present study. For example, the test plates, although they were subjected to natural flow currents of the marine environment, were not subjected to the "unnatural" flow currents of a power plant cooling system. Thus, fouling on the test plates might be somewhat different from the fouling of a cooling system. Yet the test plates offer useful indications as to what will happen in the actual cooling system and therefore they are useful for predictive planning of power plant engineers.

In the present study, variations in the abundance and species composition of fouling organisms were observed for the different construction materials. Accumulation was slow on the copper-nickel alloy plates, but was rapid and complete on the concrete and wood plates. Because the fouling plates were exposed to identical environmental conditions, the differences in fouling resistance must have been dependent upon the differences between the media. Previous research has shown the same results—Woods Hole Oceanographic Institution (1952), for example, found that copper-nickel alloy maintains its fouling resistance for 10 mo, much longer than concrete or wood.

Depth was found to have a significant effect upon the rate of fouling accumulation. For example, the dry weight of removable material from all materials placed below the surface level (1 m) was negligible except for those wood and concrete plates colonized by *Balanus crenatus*. Yet at the surface there was considerable algal and diatomaceous growth on all media except the copper-nickel alloy. The only organism which increased in density as the depth increased was *B. crenatus*, the only organism colonizing the plates at the 15.3-m level. Because these results were similar for all media and because they were corroborated by qualitative examinations made on the ropes, floats, and anchors, it appears that a cooling system intake in the Kiket Island area should be sited in water deeper than about 6 m. Based on biofouling results, the cooling system intake should not be sited at the surface because fouling is greatest at that level.

An analysis of the seasonal distribution of the fouling organisms showed that there was initially an accumulation of brown detrital film and bacterial slime on the fouling plates. Soon a filamentous algae, *Enteromorpha*, and a diatom, *Melosira*, became established. As floral density increased, greater numbers of Crustacea were observed living in the growths on the plates. Barnacle and mussel colonization of the test plates occured throughout the year, but was greatest from April through October. For mussels, at least, it appeared that a previous accumulation of fouling material was required before the mussels would attach to the test plates. Thus, it would appear that fouling control should be greatest during the spring, summer, and early fall. During late fall and winter fouling control need not be so greatly emphasized. It must be remembered that the time for maximum fouling may vary from year to year, and thus fouling control should be regulated by routine observations of larval settlement. In addition, early fouling control may help to deter col-

[5]Benson, P. H., E. L. Littauer, and N. P. Stumbaugh. 1968. Outlook for marine corrosion and fouling protection. Paper presented at Symposium on Ocean Technical Problems of the 1970's. 61st Annu. Meet., Los Ang., Calif., Dec. 1968, 42 p.

[6]Mawatari, S. 1965. Protection of power plants from biological fouling. Unpubl. rep. Research Institute for Natural Resources, Tokyo, Jap.

[7]Pomerat, C. M., and C. M. Weiss. 1946. The influence of texture and composition of surface on the attachment of sedentary marine organisms. Unpubl. manuscr.

onization by mussels, which, according to Hoshiai (1964) and Holmes (1970), are the principal fouling organisms in power plant cooling systems.

The use of intermittent chlorination as a fouling control agent has been noted by Holmes (1970), Morris (1971), and Draley (1972). In general, most investigators feel that the larvae of various marine fouling organisms are more sensitive to chronic low-level concentrations of chlorine than are the adults (Dobson 1946; Turner et al. 1948). Thus, greatest effectiveness results from repeated low-level chlorination, which either kills the larvae directly or creates an unfavorable environment for settlement.

Any fouling control scheme should maintain adequate precautions against excessive interference with organisms inhabiting the receiving water ecosystem. Chemical toxins such as chlorine are objected to as antifouling agents primarily because of the possible detrimental effects on nontarget organisms (Waugh 1964; Hamilton et al. 1970; Stober and Hanson 1974). This effect is particularly true when the treated effluent is discharged directly into the aquatic environment.

The data presented in this study can only be called preliminary. Additional tests should be run which would include at least one complete annual cycle study of subtidal fouling. Yet the present study does indicate that if the proposed plant were to be built at Kiket Island, its cooling system should be in water deeper than 6 m and should have a safe and adequate fouling control scheme. Of the different construction materials tested in this study, it would appear that copper-nickel alloy would most effectively deter fouling and that concrete and wood would be least effective.

It must be emphasized that the present study is an analysis of biofouling. Prior to the siting and final design of the cooling water intake structure, consideration must also be given to the potential effects of entrainment on zooplankton and larval and juvenile fish.

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