V CONGRESO INTERNACIONAL DE CORROSION MARINA E INCRUSTACIONES

5th INTERNATIONAL CONGRESS ON MARINE CORROSION AND FOULING

5ème CONGRES INTERNATIONAL DE LA CORROSION MARINE ET DES SALISSURES

BIOLOGIA MARINA

Barcelona, 19-23 mayo - May - mai 1980
ESPAÑA - SPAIN - ESPAGNE

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BIOLOGIA MARINA
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MECHANISM OF MICROBIOLOGICAL CORROSION

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Argentina

ABSTRACT

Among the principal metabolic products of the aerokerosene degradation by *Cladosporium resinae* the literature mentions organic acids such as citric, isocitric, ketoglutaric, etc. Through electrochemical measurements it was determined that the pH decrease caused by this fungal proliferation would not influence the pitting corrosion of Al alloys.

It could on the contrary be determined by the anionic concentration of these acids in the aqueous phase in equilibrium with the fuel. In the same terms, an interpretation is also proposed to explain the different type and magnitude of the attack observed.

We observed that, in service conditions, the only microbiological jet fuel contaminant showing high proliferation is the mentioned fungus. *Pseudomona aeruginosa* levels determined correspond to a normal contamination without proliferation evidence.

INTRODUCTION

The aim of this paper is to provide some electrochemical results which could contribute to clarify the mechanism of the microbiological corrosion of structural aluminium alloy used in the integral fuel tanks of jet powered aircrafts.

Several mechanisms have been proposed, Hedrick *et al.* (1967), Parbery (1968), Walker and Cooney (1973) being widely reported that *Cladosporium resinae, Pseudomona aeruginosa* and other microorganisms produce severe corrosion in pure culture on those alloys. In tests performed on mixed culture, *Cladosporium resinae* and *Pseudomona aeruginosa* were the only survived (Hedrick *et al.*, 1965). Metabolic products of the fuel by *Cladosporium resinae* are reported to be organic acids such as citric, isocitric, ketoglutaric, etc. (McKenzie, 1977).

EXPERIMENTAL

Potentiokinetic polarization curves of Al 99.99 % and 2024 T 351 aluminium alloy, polished up to 600 emery paper, were performed using a Tacussel potentiostat PRT 20 2X. A potential scan of 10 mV/min was applied with a Servovit-9A. A conventional Pyrex glass cell with a Pt counter electrode and a calomel reference electrode through a Luggin capillary were used. Aqueous solutions were different support electrolytes with variable concentrations of metabolites, filtered prior to each run to avoid microbiological contact with the alloy. Deaereation was performed by bubbling of 99.99 % N_2 for the anodic curves. Cathodic ones were obtained in O_2 saturated solutions.

Cultures of isolates of *Cladosporium resinae* f. *avellaneum* and *Pseudomona aeruginosa* were obtained from fuel storage tanks. They were incubated in batch in a 500 ml Erlenmeyer flask containing 300 ml of Bushnell-Haas (1941) solution diluted to 1:10 with distillate water and 50 ml of Jet A1, as only carbon source. Incubation was done at 30 ± ± 1° C.

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RESULTS

The polarization curves obtained in the aqueous phases, by triplicated runs, are shown in Figures 1 to 6.

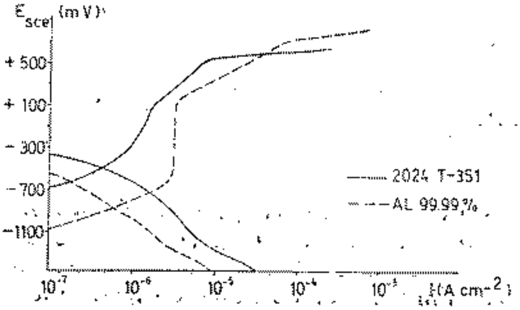

FIG. 1.—Potentiokinetic polarization of Al 99.99 % and 2024 T 351 aluminium alloy in Bashnell-Haas solution diluted to 1 : 10, *sterile solution.*

pH = 6.0

	Al 99.99 %	*2024 alloy*
E_p (mV$_{sce}$)	+ 630	+ 550
E_c (mV$_{sce}$)	— 850	— 470
E_p-E_c (mV)	1480	1020
i_c (A.cm^{-2})	6.0 × 10^{-7}	4,2 × 10^{-7}

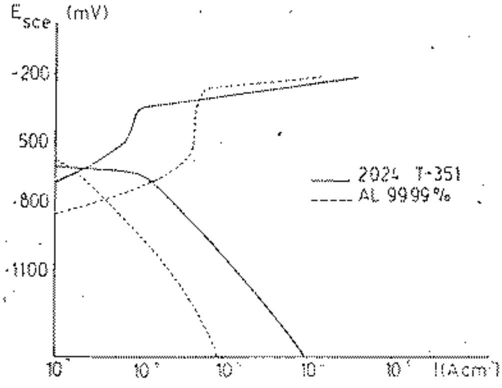

FIG. 2.—Potentiokinetic polarization of Al 99.99 % and 2024 aluminium alloy in Bushnell-Haas solution 1 : 10, incubated in the presence of mycelium of *Cladosporium resinae,* up to fungal growth at all the interface (8 days):

pH = 5.2

	Al 99.99 %	*2024 alloy*
E_p (mV$_{sce}$)	— 250	— 350
E_c (mV$_{sce}$)	— 800	— 500
E_p-E_c (mV)	500	150
i_c (A.cm^{-2})	4.0 × 10^{-7}	6.0 × 10^{-7}

From Figures 1, 2 and 3 it can be observed the aggressiveness increase, in the batch-system, inoculated with mycelium of 3 isolates of *Cladosporium resinae* as a consequence of higher metabolite concentrations. These experiences, performed using Al 99.99 % and 2024 T 351 alloy, may be compared with previous results in a batch system of bigger volume and interface area. The volume influence is shown through lower pH values for the biggest batch system: in 500 ml Erlenmeyer, at 60 days of incubation pH was 4.5 while in the Erlenmeyer of 4000 ml, at the same incubation time, pH was 4.0.

From Figures 1, 2 and 4 it can be observed that Al 99.99 % shows a better behaviour to pitting corrosion by *C. resinae* metabolites than 2024 alloy due to a larger E_p-E_c difference, in the pH range 5.2 to 8.0.

Comparison of the results of figures 3 and 4 shows the influence of the pH increase on a solution with a high concentration of metabolates of *C. resinae*:

	Al 99.99 %	*2204 Alloy*
E_p (mV sce)	— 170	— 300
E_p-E_c (mV)	250	— 50
i_c (A · cm^{-2})	2.5 × 10^{-6}	7.5 × 10^{-6}
	pH = 4.5	

$\xrightarrow{NH_3}$

Al 99.99 %	*2204 Alloy*
— 150	— 350
100	— 40
2.0 × 10^{-7}	1 0 × 10^{-6}
pH = 8.0	

As pitting corrosion probability is higher for lower E_p-E_c values, acidity does not favour it. Cathodic limiting currents are smaller.

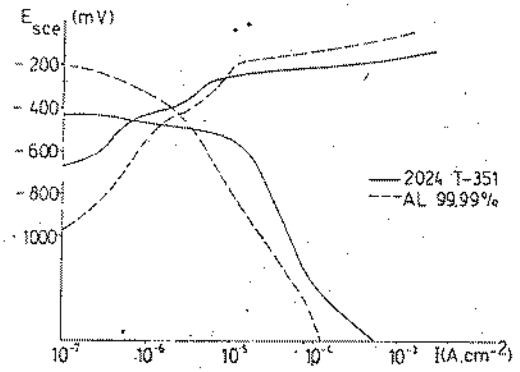

FIG. 3.—Potentiokinetic polarization of Al 99.99 % and 2024 T 351 aluminium alloy in the previous medium after 90 days incubation:

pH = 4.5

	Al 99.99 %	2024 alloy
E_p (mV$_{sce}$)	— 170	— 300
E_c (mV$_{sce}$)	— 420	— 250
E_p-E_c (mV)	250	— 50
i_c (A.cm^{-2})	2.5×10^{-6}	7.5×10^{-6}

This experience enabled us to conclude that the anion concentration of the metabolites is the controlling reagent determining pitting in Al and its 2024 alloy. This result would be in agreement with the obtained by Kaesche (1962) in the sense that pH does not seem to affect E_p of aluminium in NaCl solutions, at least for pH values between 2 and 11.

DISCUSSION

In a Parbery's paper (Parbery, 1968) concerning the role of *Cladosporium resinae* in the corrosion of the aluminium alloys, with a culture of this fungus in Bushnell-Haas nutrient solution and kerosene the following results were brought:

a) In most of the flasks, fungal adherence to the alloy was not observed.

b) Some of the aluminium pieces showed focus of corrosion, principally if fungal growth occurred in contact with the alloy.

c) Generalized corrosion was the most extensive form of attack without pitting or other signs of localized corrosion. This results were attributed to the corrosion by the organic acids derived from the fuel biodegradation by the fungus.

We performed many laboratory tests consisting on the incubation of different aluminium alloys in flasks containing contaminated Jet A1 fuel and water drained from ground fuel stor-

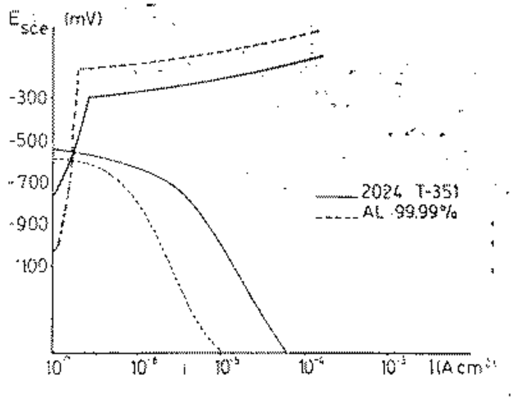

FIG. 4.—Potentiokinetic polarization of Al 99.99 % and 2024 T 351 aluminium alloy in the aqueous phase of the previous medium. Adjusted to pH = 8 by addition of NH_4HO:

	Al 99.99 %	2024 alloy
E_p (mV$_{sce}$)	— 150	— 300
E_c (mV$_{sce}$)	— 950	— 960
E_p-E_c (mV)	100	— 40
i_c (A.cm^{-2})	9.0×10^{-7}	1.0×10^{-6}

ages, the only microbian growth corresponding to *Cladosporium resinae*. The results obtained were in good agreement with Parbery's ones and with corrosion observed in contaminated aircrafts tanks.

The batch system employed was a 500 ml Erlenmeyer flask being attained pH = 4.0 as the lowest stationary value. In a previous work (Meybaum *et al.*, 1978) using the same solution in batch, but in an Erlenmeyer flask of 4000 ml, the lowest pH was 3.2. In these conditions pH decrease may be considered as a measure of the proliferation magnitude. In aircrafts, although greater interfaces kerosene-water are present, the aqueous face has never shown pH values under 4.0 even if proliferation of *Cladosporium resinae* has occurred.

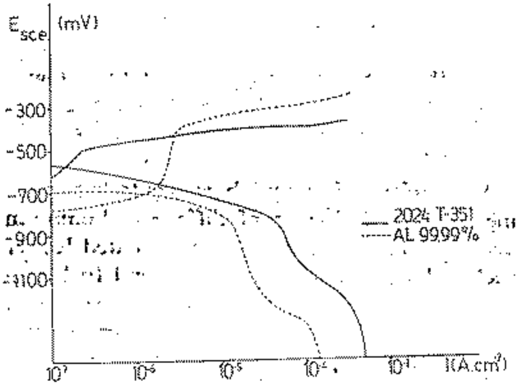

FIG. 5.—Potentiokinetic polarization of Al 99.99 % and 2024 T 351 alloy in water drained from a tank of an aircraft with a high proliferation of *Cladosporium resinae* as only contaminant grown:

pH = 4.5

	Al 99.99 %	*2024 alloy*
E_p (mV_{sce})	— 400	— 500
E_c (mV_{sce})	— 370	— 400
E_p-E_c (mV)	— 30	— 100
i_c ($A.cm^{-2}$)	7.0×10^{-6}	2.0×10^{-5}

Pitting was observed in service conditions, corresponding to E_c more anodic then E_p.

In service conditions we observed that when microbian proliferation is verified in a tank; the only microorganism grown is *Cladosporium resinae*, developed as consistent mats. A scarce biological sludge of other microorganisms could also be found but it does neither cause blockage of turbine filters nor corrosion increase.

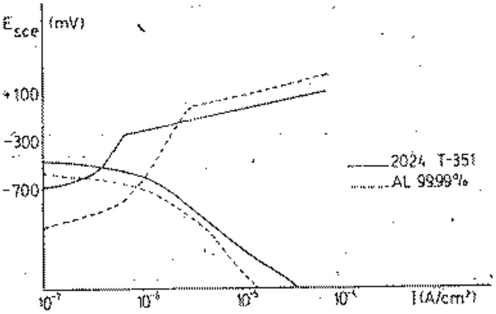

FIG. 6.—Potentiokinetic polarization of Al 99.99 % and 2024 T 351 aluminium alloy in the aqueous phase Bushnell-Haas 1:10, inoculated with 7 isolates of *Pseudomona aeruginosa*, incubated during 3 months at 25° C:

pH = 4.6

	2024 alloy	*Al 99.99 %*
E_p (mV_{sce})	— 250	0
E_c (mV_{sce})	— 350	— 650
E_p-E_c (mV)	100	650
i_c ($A.cm^{-2}$)	7.0×10^{-7}	1.0×10^{-6}

Pitting did not appear, in agreement with E_p more anodic than E_c. Slight generalized corrosion was observed corresponding to very low i_c values.

In pure culture of *Pseudomona aeruginosa* in the same support electrolyte it was also observed a decrease of the E_c at a high metabolic concentration (Fig. 6) but in fuel tanks of aircrafts the count of *Pseudomona aeruginosa* was low. All these results could be interpreted as a function of electrochemical parameters determined by us in different support electrolytes (nutrient solution and drainage water from aircrafts) (Schiapparelli *et al.*, 1977; Meybaum *et al.*, 1978; Meybaum and Schiapparelli, in press).

From the oxygen limiting currents determined and considering the corresponding corrosion potentials (E_c), it could be concluded that when proliferation is absent, low i_c values are measured and the uniform corrosion observed occurred at an E_c which is lower than the pitting potential (E_p). For longer incubation periods the difference between E_c and E_p decrease, tending to zero for high metabolite concentrations in the medium, as can be seen in Figure 5. Simultaneously, we determined increasing corrosion rates, in the present as in previous works, in *Cladosporium resinae* cultures. This would imply that for high metabolite concentrations pitting corrosion would occur with a high corrosion rate. Previously we demonstrated (Meybaum and Schiapparelli, in press) that for incubation times longer than 24 days, i_c values were 100 times higher than in sterile media and E_c equal to E_p. In those cases pitting occurred with current densities increasing with the metabolite concentration.

A region of an alloy in contact with a colony would be exposed to the highest local metabolite concentration. This would explain the localization and type of attack at different areas, and pitting under fungal mats (Parbery, 1968).

This uneven behaviour would be enhanced considering the differential aeration created by the fungal mat on the alloy.

The general chemical reaction controlling the process could be the following:

$$nX^- + Al \longrightarrow Al\ Xn^{-(n-3)} \xrightarrow{H_2O} Al(HO)_3 + + 3H^+ + nX^-$$

X^- being the aggressive anion of metabolic products.

The compound formed by reaction between the anion and the aluminium would be of the non-stechiometric type with the possibility of activating the passive aluminium (Parbery, 1968). The acidity of the medium produced by the hydrolysis step would be enough to avoid the $Al(OH)_3$ precipitation and its pasivating action.

CONCLUSIONS

The microorganisms produce organic acids by oxidation of hydrocarbons, which are responsible of the E_p decrease.

The decrease in pH caused by microbial proliferation is not the controlling factor in the pitting corrosion process.

ACKNOWLEDGEMENTS

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THE INFLUENCE OF SULPHATE REDUCING BACTERIA ON THE ELECTROCHEMICAL BEHAVIOUR OF STEEL IN SEA WATER

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SUMMARY

The electrochemical behaviour of SAE 1010 carbon steel in sea water or 0.5 M sodium chloride solutions is studied in the presence of sulphate reducing bacteria and different concentrations of sulphides. A cathodic current increase can be observed in both cases. Pitting attack can be detected in a range of potentials where passivity is usually found for mild steel in sea water. A marked decrease of the pitting potential can be determined for low concentrations of sulphides or in the presence of sulphate reducers. The influence of oxygen levels is also described.

INTRODUCTION

There is a general agreement on the importance of sulphate reducing bacteria in the microbiological corrosion of iron and steel in anaerobic conditions.

A copious literature on this subject has been developed since Von Wolzogen Kuhr and Vander Flugt elaborated the cathodic depolarization theory at the beginning of the 30's, to explain the corrosion of buried iron structures in waterlogged soils in the vicinity of Amsterdam (1). This theory attributed to sulphate reducing bacteria the capacity of accelerating the cathodic reduction of hydrogen through their ability to use hydrogen by means of an especific enzimatic system.

In spite of the numerous works supporting this theory, especially with reference to the direct participation of the bacteria in the reaction, during the last years several works have emphasized the possibility of an indirect role of the microorganisms through the production of different products like sulphides or hydrogen sulphide that would originate the corrosion process.

In sea environment the conditions are very different from those ocurring in waterlogged soils. Notwithstanding this, it has been pointed out the increment of corrosion rates observed in polluted sea waters where the conditions of the medium are dissimilar to those encountered in open sea (2). This increase in the corrossiveness of medium is greatly influenced by the variety of microbiological species present, temperature variations and specially to the existance of compounds of aggressive nature (generally sulphur compounds) originated in the industrial activity (3).

In this work we will try to establish the importance of sulphate reducing bacteria in the corrosion of marine steel in sea water comparing the effect of these microorganisms and that of different levels of sulphide on passivity, in the presence or absence of oxygen. Besides the study of the cathodic reaction, we will go deep in the comprehension of the anodic reaction narrowly related to the localized corrosion processes observed for mild steel in sea water.

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EXPERIMENTAL

Sulphate reducing bacteria isolated from fuel storage tanks were used. The samples correspond to sludge present in the bottom of ships tanks, where small amounts of water were present.

The samples were inoculated in Baars medium of the following composition:

KH_2PO_4	0.5 g
NH_4Cl	1.0 g
$CuSO_4$	1.0 g
$MgSO_4 \cdot 7H_2O$	2.0 g
Sodium lactate	3.5 g
Water	1 dm³

The medium is sterilized by autoclaving and the pH adjusted to 7.0. Samples were incubated at 25° C in anaerobic BBL Gas Pack Jars (No. 60465).

Electrochemical assays were made with artificial sea water.

For the experiments microorganisms were incubated in Erlenmeyers of 500 ml containing 100 ml of solidified Baars medium (1.5 % agar) on the bottom and covered with 500 ml of artificial sea water. Erlenmeyers were incubated at 25° C in the anaerobic jars. After an adequate growth was obtained (c.a. one week) the supernatant liquid was transferred to the electrochemical cell in a nitrogen atmosphere.

In the experiments using different concentrations of sulphides, a stock solution of sodium sulphide (0.1 M) + (0.5 M) ClNa was used. The experimental concentrations were obtained by dilution in 0.5 M ClNa or artificial sea water, with a previous deaereation with pure nitrogen. The pH of the solutions were adjusted to 8.0 with ClH 0.1 N.

Iodimetric titrations were used not only to determine the sulphide concentration in sulphate reducers cultures but also to verify the sulphide concentration of the dilutions.

The cell employed for electrochemical measurements was a double wall Pyrex glass cell already described in a previous work (4). Pt wire was used as counter electrode. The working electrodes consisted in rectangular shape 1010 SAE carbon steel probes of c.a. 1 cm² exposed area. Prior to their use they were alumina polished and degreased with acetone A.R. Potential were referred to saturated calomel electrodes through a Luggin capillary.

A current of 50 μA/cm² was applied during five minutes previously to each experiment in order to reduce the oxidated surface. Polarization curves were performed beginning at —850 mV in anodic direction changing the potential in steps of 20 mV/s.

RESULTS

Figure 1 shows typical polarization curves of 1010 SAE steel in deaerated 0.5 M NaCl solution or artificial sea water. In this curve we observed three zones: the first one corrresponding to an active zone, a second one of passivity and at potentials more positive than —580 mV, there was a big increase in the current associated to a pitting phenomenon.

Potentiostatic polarization curves obtained without nitrogen deaeration are shown in Figure 2. Similar values to those observed in Figure 1 were obtained for pitting potential. As a consequence of the potential value corresponding to the zero of current identical values are obtained for E_{corr} and E_{pit}.

The effect of sulphide addition at different oxygen levels on the passivity of SAE 1010

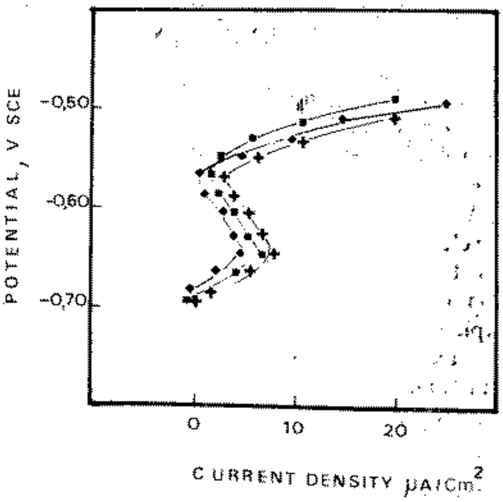

Fig. 1.—Potentiostatic polarization curves for SAE 1010 steel in de-aerated solutions (pH 5.0). (●) (■) artificial sea water; (+) ClNa 0.5 M.

steel is shown in Figure 3. In these experiments the working electrode is potentiostatized at —620 mV in aerated or deaerated solutions. Low anodic currents are obtained at —620 mV in deaerated solutions. Similar currents but cathodic are found at the same potential in the case of aerated solutions. Both currents correspond to the passivity zone of the metal. A different behaviour can be observed after 2 ml of 10^{-3} M SNa_2 + 0.5 M ClNa was added at pH 8.0. A marked increment in the current towards anodic values can be observed in deaerated solutions. No appreciable increment was observed in the other case. Only when levels of 10^{-2} M of SNa_2 + + ClNa 0.5 M are added, a noticeable increment of the current is obtained. The observation of the electrodes after the experiment revealed the presence of pitting.

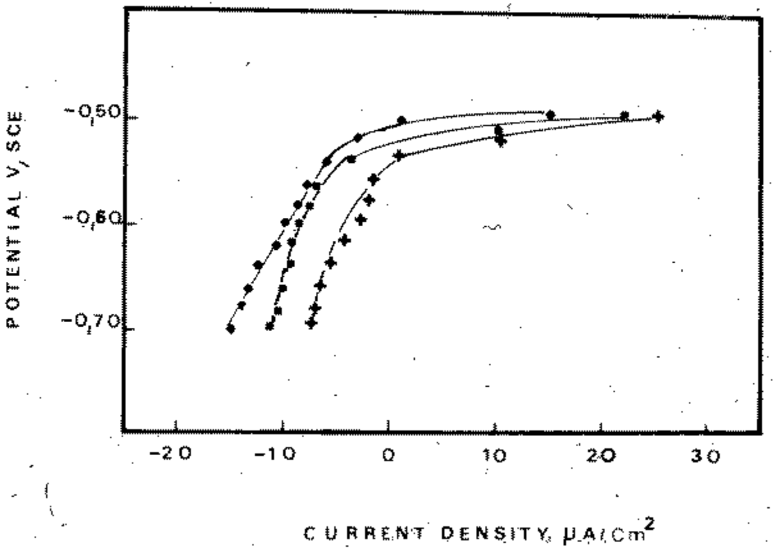

FIG. 2.—Potentiostatic polarization curves for SAE 1010 steel in aereated solutions (pH 8.0). (◆) (■) artificial sea water; (+) ClNa 0.5 M.

Polarization curves in the presence of sulphate reducing bacteria in sea water are shown in Figure 4. Sulphide concentrations in these solutions correspond to 10^{-3} M and the pH was 8.0. A marked decrease of the pitting potential is observed in these solutions with reference to sterile sea water. A comparison with a polarization curve obtained at the same pH in SNa_2 10^{-3} M + 0.5 M NaCl solution is also made. An increment of the cathodic current can be observed in both cases as it has been already described in the literature.

DISCUSSIONS

Polarization studies made by several authors, using mild steel in the presence of sulphate-reducing bacteria show that the active participation of those microorganisms in the corrosion process is unquestionable (5, 6). Nevertheless, in spite of the abundant literature on this subject it is not yet possible to asses if the role of the sulphate reducers is direct (acting on the kinetics of the cathodic reaction) or indirect (due to the activity of a product like H_2S or sulphide) (7).

Supporting the direct participation of the bacteria in the process, polarization work by Horvath (8) and Booth and Tiller (9) shows that greater cathodic currents are obtained in the presence of microorganisms than in their absence for the same shift in potential. Further experimental work restricted this cathodic activity to hydrogenase positive strains of the gen. Desulfovibrio in a direct relation to their capacity of utilizing hydrogen to perform the «dessasimilatory reduction of sulphates» (10).

Otherwise, the depolarizing action of the bacteria with exclusion of sulphate as electron acceptor was demonstrated by Iverson using a redox dye (benzyl viologen) to show that cathodic depolarization may not be necessarily coupled to sulphate reduction (11).

More recently, King and Miller attributed the depolarizing effect during the corrosion process to the action exerted at the surface by solid ferrous sulphide particles which could act as cathodes in corrosion cells (12).

Notwithstanding all these information supporting the primary role of the bacteria on the process through the modification of the cathodic kinetics, several aspects of the direct microorganisms participation remain unclear: *a)* the ratio found for total iron corroded to ferrous-sulphide produced vary from 0.9 to nearly 50 instead of 4 as was established by the theory (7); *b)* other hydrogen utilizing bacteria like nitrate reducing bacteria that should stimulate corrosion by a similar mechanism in anaerobic conditions shows no cathodic depolarization effect. The same can be said for methane bacteria (13); *c)* anodic polarization experiments as well as thermodinamic assumptions based on Pourbaix diagrams of the system Fe/S/H_2O show that the action of sulphide and H_2S on the corrosion process can not be disregarded (14).

Recent research work of Costello (15) using hydrogenase active strains of desulfovibrio shows conclusively that the depolarizing effect may be ascribed to the cathodic activity of hydrogen sulphide.

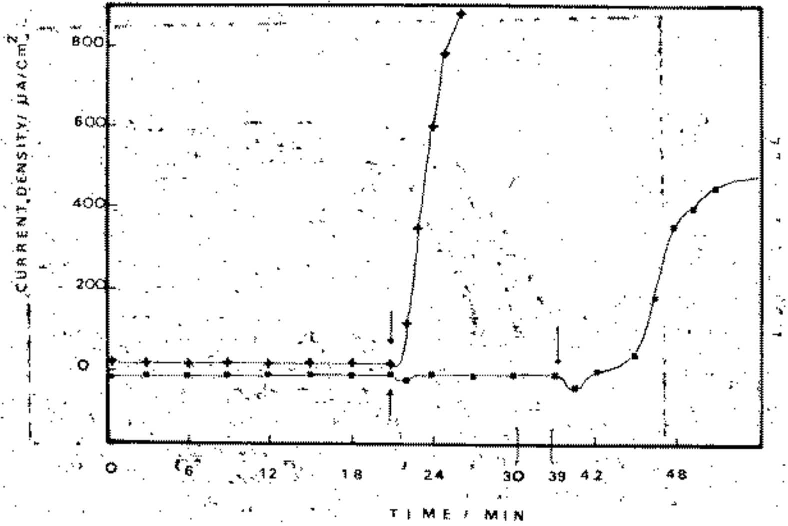

FIG. 3.—Effect of the sulphide addition on the passivity (at —0.62 mV SCE) of SAE 1010 steel. (+) deaerated; (■) aereated. The arrows indicate sulphide addition.

The cathodic behaviour of this substance may be represented by the over-all reaction:

$$2H_2S + 2e^- = H_2 + 2HS^-$$

The hydrogen evolution mechanism may result a function of HS^- concentration and/or the H_2S/HS^- ratio (16).

In contrast with the numerous studies and considerations made on the cathodic reaction the study of the anodic behaviour of iron and steel in the presence of sulphate reducers has been seldom mentioned.

Wranklin and Spruit (17) pointed out that under autothropic conditions no significant cathodic depolarization occurs being of greater

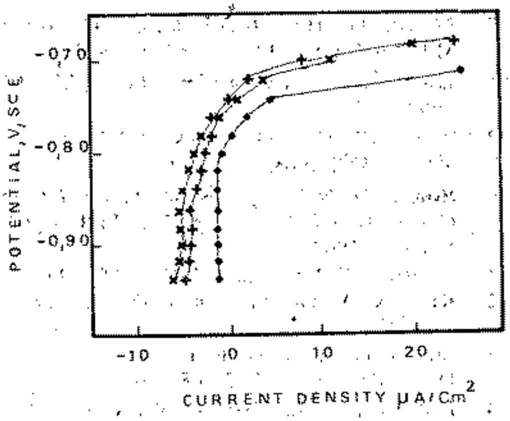

FIG. 4.—Potentiostatic polarization curves for SAE 1010 steel in the presence of sulfate reducing bacteria: (×) (+) (10^{-3}M sulphide pH 8.0). (●) SNa_2 (10^{-3}M pH 8.00).

importance the anodic depolarization effect caused by the sulphides. These facts were confirmed later by Horvath through polarization studies using active cultures of sulphate reducing bacteria.

Although the sea environment conditions may differ greatly from those encountered in buried iron srtuctures in some circumstances, like those found in polluted harbour waters or even in ship fuel storage tanks, the corrosion process may be conditioned by the activity of sulphate reducing bacteria.

We have recently pointed out that in the bottom of ship storage tanks where sea water lay down with sludge the redox characteristics expected may favour the activity of sulphate reducers (18).

These conditions can be compared to those already found in fuel-water systems especially in the case of navy fuels of similar composition of jet fuels. We have isolated in samples of this kind aerobic bacteria of gen. Pseudomonas, fungus like *Cladosporium resinae* and yeast of the gen. *Candida*. In all samples sulphate reducers were present.

The localized form of attack, especially under the form of pitting is frequently found in the case of aluminium and its alloys in fuel-water systems. We have emphasized the importance of electrochemical parameters like corrosion potential and pitting potential in relation to microbiological variables to explain the electrochemical behaviour of those metals in fuel-water systems (19).

Recent research on the passivity breakdown of pure iron and AISI 4340 in 0.5 M NaCl solutions shows the importance of pitting potential to study the electrochemical behaviour of these metals (20).

Our experiments show that the passivity of 1010 carbon steel is strongly affected by the addition of small concentrations of sulphides presenting localized forms of attack at potential values commonly corresponding to passivity. This behaviour can be interpreted in terms of the pitting potential decrease observed experimentally from the potentiostatic polarization curves.

Active cultures of sulphate reducing bacteria show that levels of sulphide in the order of 10^{-3} are usually found showing an identical electrochemical behaviour to that previously observed with sulphide solutions. In all cases the pitting potential was markedly decreased and the corrosion potential shows values near those of the pitting potential in this medium. An increment of the cathodic current can be observed in concordance with all those findings established previously by the literature.

A complementary effect that remains to be studied in detail can be observed in aerated solution where higher concentrations of sulphides are necessary to break the passivity that those needed to produce equal effect in deaerated solutions (Fig. 3). This effect is of special interest regarding the varying conditions found in the sea environment or in ships storage tanks where oxygen levels can be greatly modified by biological or physical factors.

From our experiments it can then be concluded that:

i) The electrochemical behaviour of 1010 steel in artificial sea water or 0.5 M NaCl solution is similar in the presence of active sulphate reducing bacteria to that encountered in sulphide solutions of low concentrations.

ii) Different levels of sulphides are needed to produce the same effect on passivity in the case of deaerated solutions or in the presence of oxygen.

iii) A cathodic current increment can be observed in both cases (in the presence of sulphate reducers or sulphide solutions) but the electrochemical behaviour of 1010 steel in sea water can be mainly interpreted in terms of the anodic reaction. This behaviour is characterized by a strong modification of the passivity observed experimentally by a pitting potential decrease.

Further research work remains to be done in order to establish the activity of several strains of sulphate reducing bacteria of different enzymatic activity as well as the interrelation with other aerobic microorganisms usually present in sea water.

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THE IDENTIFICATION OF SOME MARINE FOULING ORGANISMS AND THEIR BREEDING SEASON AT LATTAKIA PORT

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Syria

INTRODUCTION

The only animals that could surpass man in the abuse of his microenvironment are the wood-boring marine organisms, which, with their continual rasping would eventually change their natural dwellings into graves when the wood content can not support them any longer.

These ubiquitous pests level a strong blow at the local merchant and fishing wooden boats. The lack of information regarding these animals at the Syrian shores, and the urgency to minimize their effect prompted this research. The pursual of literature on wood-boring organisms presented utter confusion till the work of TURNER (1966), and later on, of NAIR and SARASWATHY (1971), and GOSNER (1971).

The aims of this research were to compare the resistance of local pine *(Pinus brutia)* and imported mahogany *(Swietenia mahagoni)* to borers; the identification of these borers; and lastly, to determine the breeding season of the borers identified.

MATERIALS AND METHODS

A small testing station was constructed (figure 1) from two floatation drums joined to suport the test racks. The panels used were 30 × 15 × 1.5 cm and the method of TURNER (1959) was adopted whereby two sets of panels, twelve each, of local pine and imported mahogony for each month were used. A control panel of each kind of timber was tested for a period of one month through the year to determine the breeding season, while the previous test panels were numbered from one to twelve, and one was removed each month to access the degree of infestation. The racks were mounted so that the panels were two meters from the surface and the testing station was moored in the White Harbor, north of Lattakia where the average depth was approximately three meters. All test panels were air dried to a constant weight before and after the test period in a room with a relative humidity of 42 %. For morphological studies, the specimens were collected after being stunned by placing the test panel in fresh tap water, after being broken in half. This caused the molluscan borers to partially come out of their tunnels and were gently pulled out and placed in fixing solution (70 % alcohol). This method, invariably, led to separate the body at the pallet collar.

The crustacean borers were collected by removing the panel from the sea and allowing it to air dry for a few minutes which caused the small borers to come out of their tunnels, and were directly placed in the fixing solution.

RESULTS

1. COMPARISON OF THE RESISTANCE OF LOCAL PINE AND IMPORTED MAHOGANY TO ATTACK BY BORERS

The test panels were lifted after completion of the test period, air dried, weighed, and the percentage weight loss calculated (tables 1 and 2). The results are also represented in

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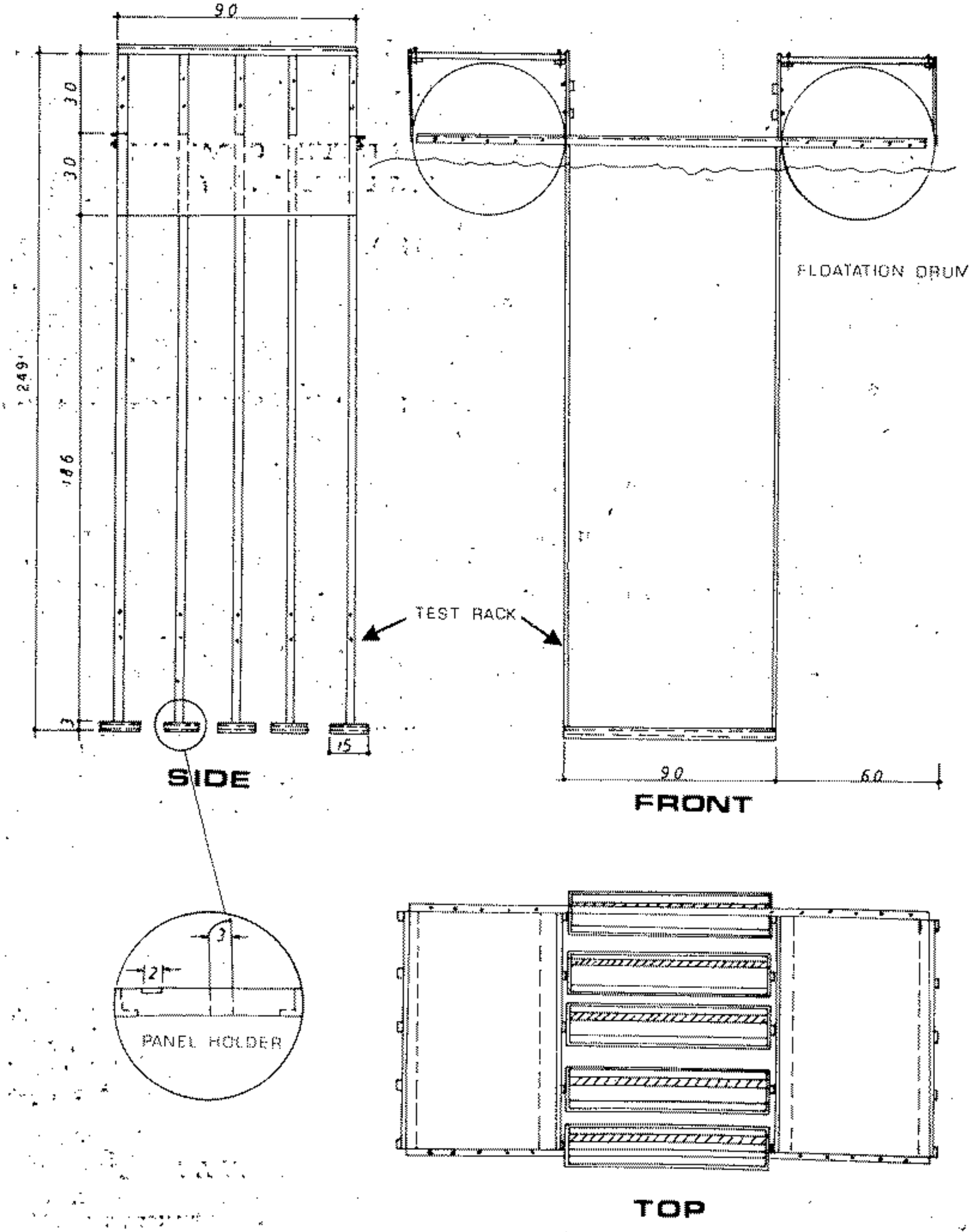

FIG. 1.—Testing station.

figure 2. The number of attacks were counted on all surfaces of each panel using a stereomicroscope (× 12). It was observed that two types of tunnels existed. The first was due to a crustacean with a slanted point of entry, and ran along the surface for 2-3 cm, with several pores that interconnected the tunnel with the sea (fig. 3). The second type was due to a

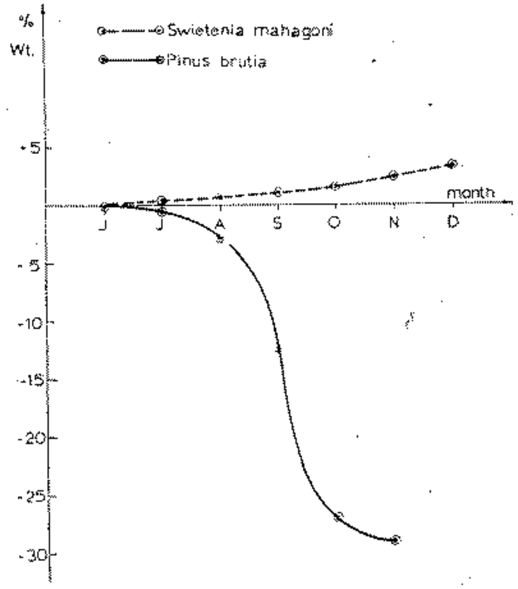

FIG. 2.—The percent weight loss and gain by local pine (Pinus brutia) and imported mahogany (Swietenia mahagoni) placed in the sea for six and seven months respectively.

FIG. 4.—The molluscan point of entry with the calcareous material shown.

mollusc and had what seemed to be two adjacent entry points and ran deep in the panel (figure 4). X-ray photography was used to measure the extent of attack and follow the tunnels lined with a calcareous material (fig. 5). The pine panels were completely destroyed and lost after six months, whereas the mahogany panels stayed intact (figs. 6 and 7). The number of attacks per panel is summarized in table 3. The mahogany panels were fouled by Bryozoan communities as well as sedentary polychaets.

2. MORPHOLOGY OF THE ISOLATED BORING ORGANISMS

2.1. *Crustacean borers:* The organism isolated had a segmented body with seven peraeonal (thoracic) somites and six pleonal (abdominal) somites. The pleotelson had three

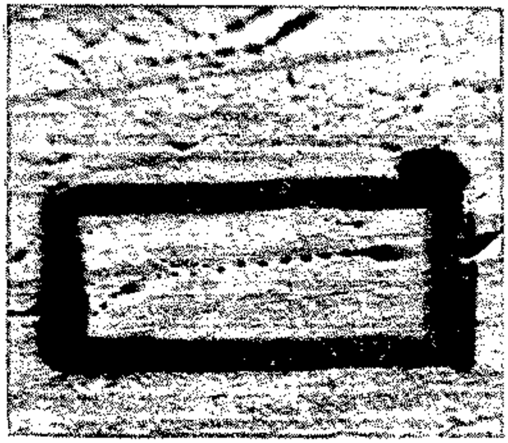

FIG. 3.—Tunnel of the crustacean borer showing the slanted point of entry and pores.

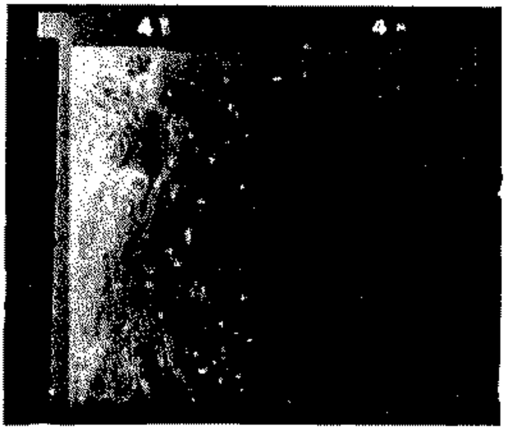

FIG. 5.—X-ray photographs of pine (4P) and mahogony (4M) test panels after four months in the sea.

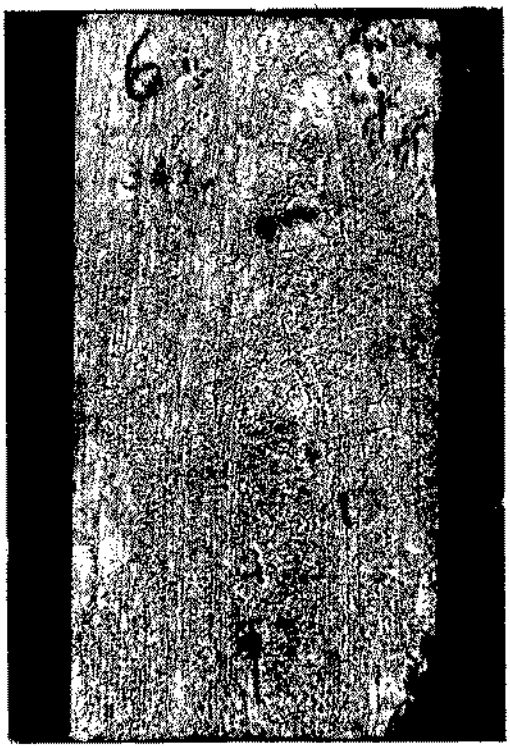

FIG. 6.—Pine panel after six months test period.

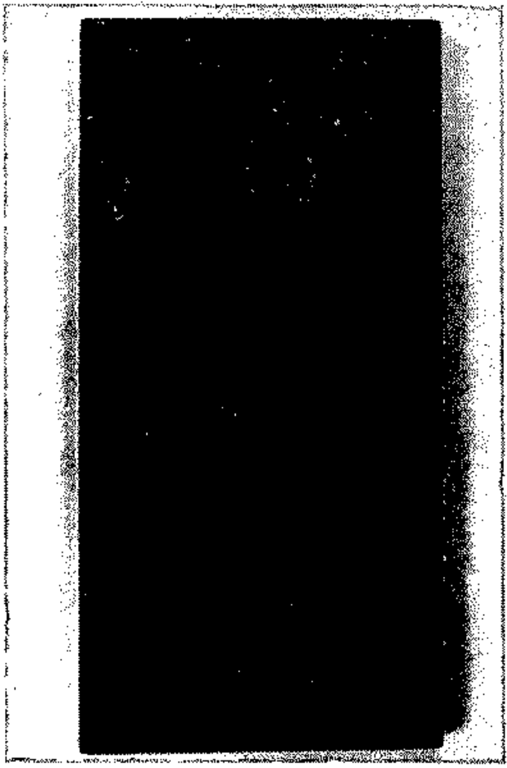

FIG. 7.—Mahogany panel after six months test period.

TABLE 1

PERCENTAGE WEIGHT LOSS OF LOCAL PINE ("PINUS BRUTIA")

No.	*Test period (month)*	WEIGHT (gm)		*Percentage weight loss* (%)*
		Before	*After*	
1	1	292	292	0
2	2	308	306	— 0.65
3	3	280	272	— 2.86
4	4	280	246	—12.14
5	5	291	212	—27.15
6	6	282	200	—29.1
7-12	Completely destroyed.			

* (—) indicates weight loss; (+) weight gain.

TABLE 2

THE PERCENTAGE WEIGHT GAIN OF IMPORTED MAHOGANY ("SWIETENIA MAHAGONI")

No.	Test period (month)	WEIGHT (gm) Before	WEIGHT (gm) After	Percentage weight gain (%)
1	1	401	401	0
2	2	393	395	+0.51
3	3	405	409	+0.99
4	4	405	410	+1.23
5	5	400	406	+1.50
6	6	400	411	+2.75
7	7	401	414	+3.24
8-12	Discontinued due to the destruction of the pine panels.			

TABLE 3

THE SUSCEPTABILITY OF "PINUS BRUTIA" AND "SWIETENIA MAHAGONI" TO BORERS

No.	Test period (month)	NUMBER OF ATTACKS CRUSTACEA P. brutia	CRUSTACEA S. mahagoni	MOLLUSC P. brutia	MOLLUSC S. mahagoni
1	1	97	0	81	0
2	2	405	0	106	0
3	3	985	0	130	0
4	4	TNTC *	0	146	0
5	5	TNTC	0	TNTC	0
6	6	TNTC	0	TNTC	0
7-12	Discontinued due to destruction of *P. brutia* panels.				

* Too numerous to be counted.

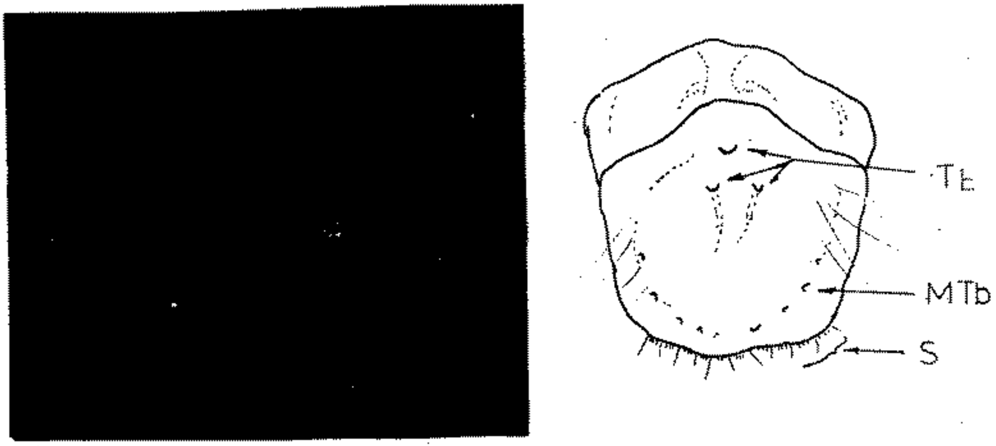

FIG. 8.—A photograph of the crustacean isolated and a drawing showing the details of the pleotelson. Tb (tubercles), MTb (marginal tubercles), S (setae).

tubercles. The peraeon had seven pairs of peraeopods, there were two pairs of antennas, with peduncular segments ending in a multi-articulate flagella. The first antenna was shorter and with three peduncles, while the second had five. The flagellum of the second antenna had five articles. The pleotelson, when viewed with incident-light microscope, showed three central tubercles and many, not very distinct, marginal ones. The setal arrangement had groups of three small marginal pleotelsonal setae separated by a larger one (fig. 8).

2.2. *Molluscan borers:* So-called «ship worms» with varied length form 2-14 cm were isolated from test panel No. 5 (table 3). Close examination of the point of entry revealed that it is a single elongated hole in the timber containing two calcareous tubes (fig. 4) that joined after 1-2 cm to contain the body. Alongside the two siphons, there were two segmented pallets (fig. 9) with the segmented body measuring 8-9 mm and the stalk 5 mm. However, it was seldom that an intact pallet could be removed due to its fragility. The two valves had a prominent posterior median and posterior (auricle) lobes. The span between the anterior and the posterior lobes was approximately 5 mm (fig. 10) where the body measured 4.5 cm, although extensive shrinkage was observed upon immersing the panels in tap water and then fixing solution. Figure 11, is a poor

TABLE 4

THE NUMBER OF CRUSTACEAN AND MOLLUSCAN ATTACKS ON PINE ("PINUS BRUTIA") PANELS

	NUMBER OF ATTACKS	
Month	*Crustacean*	*Molluscan*
January	0	2
February	0	2
March	12	16
April	97	81
May	305	24
June	577	15
July	140	9
August	1359	17
September	458	49
October	21	130
November	20	136
December	12	4

TABLE 5

SURFACE TEMPERATURE VARIATIONS AVERAGED MONTHLY

Month	*Average surface temperature (°C)*
January	17.4 ± 0.8
February	16.8 ± 1.4
March	18.1 ± 0.6
April	20.5 ± 1.1
May	21.5 ± 0.9
June	24.4 ± 1.3
July	27.0 ± 2.7
August	27.5 ± 1.8
September	27.4 ± 1.2
October	25.2 ± 1.7
November	21.2 ± 1.9
December	19.4 ± 0.8

FIG. 9.—The segmented pallets showing the cone in cone, funnel shaped segments, with mm scale.

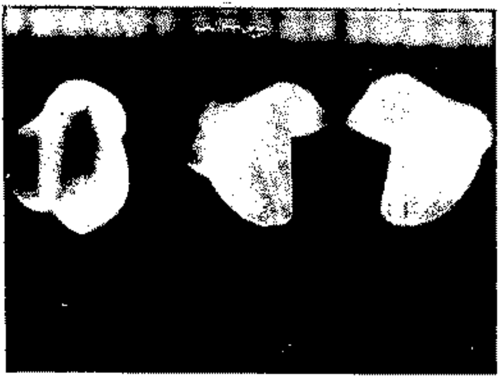

FIG. 10.—A frontal view of a pair of valves, right, and an inside view showing the condoyles, left.

photograph of the entire organism after we artificially joined the body to the collar and the pallets placed alongside the two siphons.

3. DETERMINATION OF THE BREEDING SEASON

The number of attacks on each of the monthly placed control panels was counted (table 4). The results are represented in figure 12. The surface temperature was taken daily and averaged for each month and the results are shown in table 5 and figure 13.

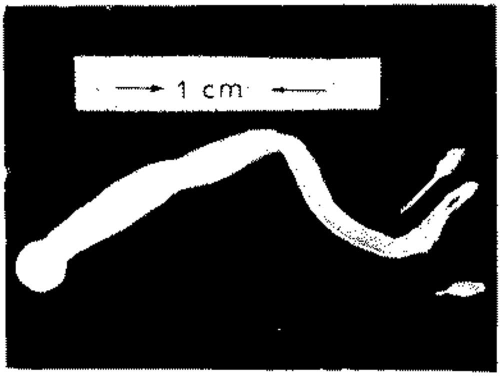

FIG. 11.—A view of the entire mollusc isolated and artificially joined at the pallet collar. This poor photograph, due to improper lighting, shows the two siphons and the broken, segmented pallets are placed alongside the collar. A scale with 1 mm divisions is in the background.

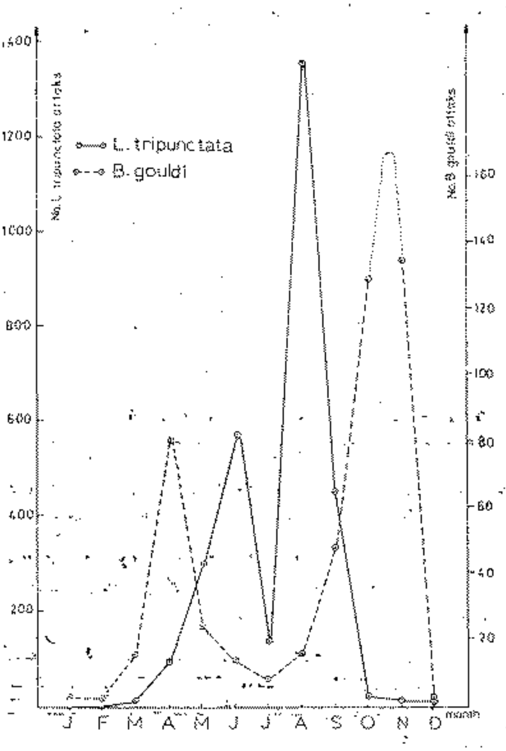

FIG. 12.—The breeding seasons of *Limnoria tripunctata*, and *Bankia gouldi* at Lattakia.

DISCUSSION

The results of the comparison studies on the resistance of local pine *(Pinus brutia)* and the imported *Swietenia mahagoni* to marine borers at the White Harbor clearly indicate the superiority of the latter.

Although tests were stopped at six months, the weight loss of local pine (fig. 2) versus the gain in the imported mahogany, which is due to the deposition of sedentary polychaets and Bryozoan colonies, as well as the X-ray photographs (fig. 5) clearly show that for all practical purposes, the local pine is almost completely destroyed with heavy infestation after three to four months. On the other hand, *S. mahagoni* survived at least seven months without a single attack by marine borers.

The crustacean specimens isolated in the gulf of the White Harbor at Lattakia, with their three tubercles on the pleotelson and the five articulated flagellum of the second antenna indicates that this borer is *Limnoria tripunctata* according to MENZIES (1957) and SCHULTZ (1969). The setal arrangement fits the assigned species as also shown by MENZIES (1959).

Due to the difficulty in obtaining intact molluscan specimens, we had to disect the panels in order to obtain the siphons and pallets. The segmented pallets (fig. 9) with the cone in cone funnel shaped units was indicative of the subfamily *Bankiinae* (TURNER, 1966), and along with the general morphology of the valves, it was tentativelly identified as *Bankia gouldi*. It should be noted that the use of shell characteristics in classification has been proven unsatisfactory; MILLER (1922), NAIR and SARASWATHY (1971), due to the diversity of their shapes among the same species.

Each of the identified boring species had

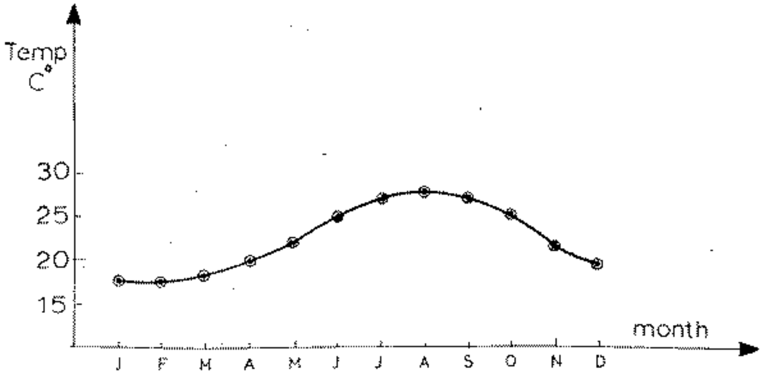

FIG. 13.—The surface temperature variation at a northern port of Lattakia taken five centimeters below the surface.

two distinct, non-coinciding, breeding seasons. *L. tripunctata* peaked in both June and August, while *B. gouldi* peaked in April and mid-October (fig. 12). It is interesting to note that both species shared minimal boring activity in the months of January and February. *L. tripunctata* seems to be more sensitive to temperature and shows maximal activity when temperature is in the higher twenties (°C). On the other hand, *B. gouldi* seemed to lack all boring activities when temperatures dipped below 20° C (fig. 13).

ACKNOWLEDGEMENT

The author would like to thank Dr. A. W. SHAHEED and Dr. A. H. MANSOUR for allowing this research to be possible; and to Dr. H. KHAROUF and Dr. A. HAMWI for their assistance in the literature search and assignement.

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FOULING PREVENTION OF LOCAL "PINUS BRUTIA" BY SHIPWORMS, "LIMNORIDII" AND OTHER MARINE FOULING ORGANISMS

DR. AYMAN HABAL *

Syria

INTRODUCTION

For many centuries, the craftsmen of the Syrian shore city of Tartous, and Arwad Island, have been known for their skills in building fishing boats and medium-sized, one and two-masted sail ships. This has grown in the late seventies into a multi-million dollar industry (1). However, due to the exorbitant increase in imported timber prices, Syrian craftsmen have turned more and more to use local pine timber *(Pinus brutia)* in their industry although this type of timber — in its untreated form — is not suited for this purpose (2). The only means of protection against borers was their use of a mixture of tar and pure sulphur powder below several layers of paint.

A good deal of work on *Pinus silvestris* (3) and other types of wood (4) have been carried out using fractions of creosotes, inorganic salts, contact insecticides, and other toxic chemicals. However, to be effective, creosote retention of 160-180 kg/m³ was needed. On the other hand, copper containing mixtures yielded good results with only 7 kg/m³ retention and 0.9 kg/m³ of gamma-benzene hexachloride (3).

The purpose of this research was to asses the value of these toxic chemicals, as well as newer compounds, to prevent borer attack on local *Pinus brutia* since this variety showed minimal resistance to borers' attack, where a test panel would be completely destroyed within 4-5 months (2) (fig. 1).

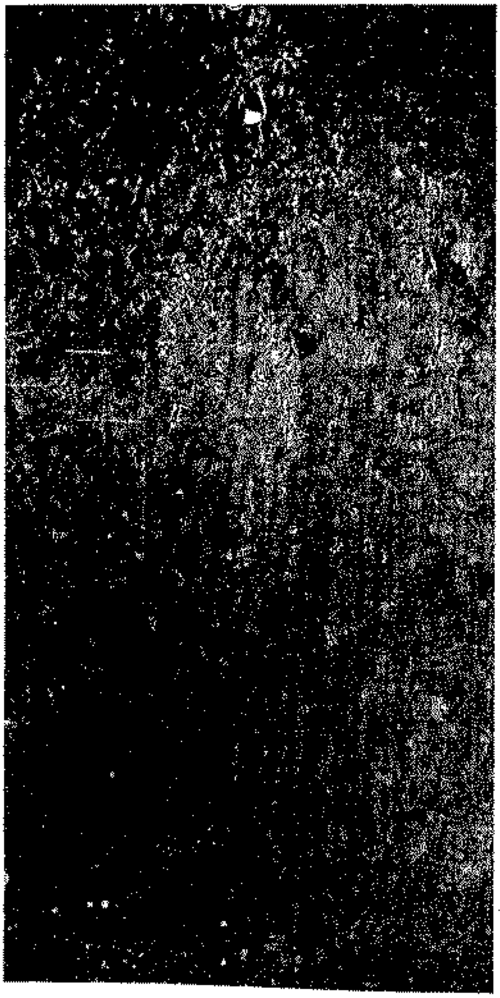

FIG. 1.—Test panel of untreated local *Pinus brutia* after five months in the sea off Lattakia.

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TABLE 1

THE COMPOSITION OF THE INORGANIC SYSTEMS TESTED

SYSTEM			
	COMPOSITION		*Final Concentration (%)*
Code	*Chemical*	*Weight (g/l)*	
AA	$CuSO_4 \cdot 5H_2O$	8.20	2.0
	As_2O_3	3.15	
	NaOH	3.50	
	NH_4OH	6.15	
AB	$CuSO_4 \cdot 5H_2O$	33.0	10.0
	$K_2Cr_2O_7$	40.0	"Double Treatment Procedure"
	As_2O_3	27.0	
AC	$CuSO_4 \cdot 5H_2O$	15.0	3.0
	$K_2Cr_2O_7$	15.0	

MATERIALS AND METHODS

The same testing station used in the study to identify borer species and their breeding seasons at Lattakia Port (fig. 2) was employed. Test panels of local *Pinus brutia* 10-13 × × 7 × 1.5 cm were impregnated by means of immersion in a hot solution of the desired treating media kept at 70° C for 35-40 minutes, followed by a quick transfer to a cold solution of the same media and kept in it for 10 minutes. An alternative method which produced the same results was to keep the treated panel in the same hot solution and cool the entire vessels. This method, however, was not employed since it proved to be too slow. The panels were air dried prior and after treatment in a room with relative humidity of 42 %. There was a minimum of 5-6 duplicate panels of each testing media, one was lifted every three months for the first year, then one every six months for the remainder of the panels used. No pre-leaching of the treated panels was performed prior to placing them in the sea. At the end of the test period the panels were lifted, washed, dried and the degree of infestation assessed by means of direct count of the number of tunnels of *Limnoria tripunctata,* and points of entry of *Bankia gouldi.* X-ray photography was also employed (figures 3-5). The following groups of toxic chemical systems were studied, and all tests commencet early in March 1976 and some lasted to mid 1979.

1. INORGANIC POISONS

Three systems were used with concentrations ranging between 2.5-10 %. Table 1 summarizes the composition of systems used.

2. PESTICIDAL POISONS

The following three systems were used (table 2).

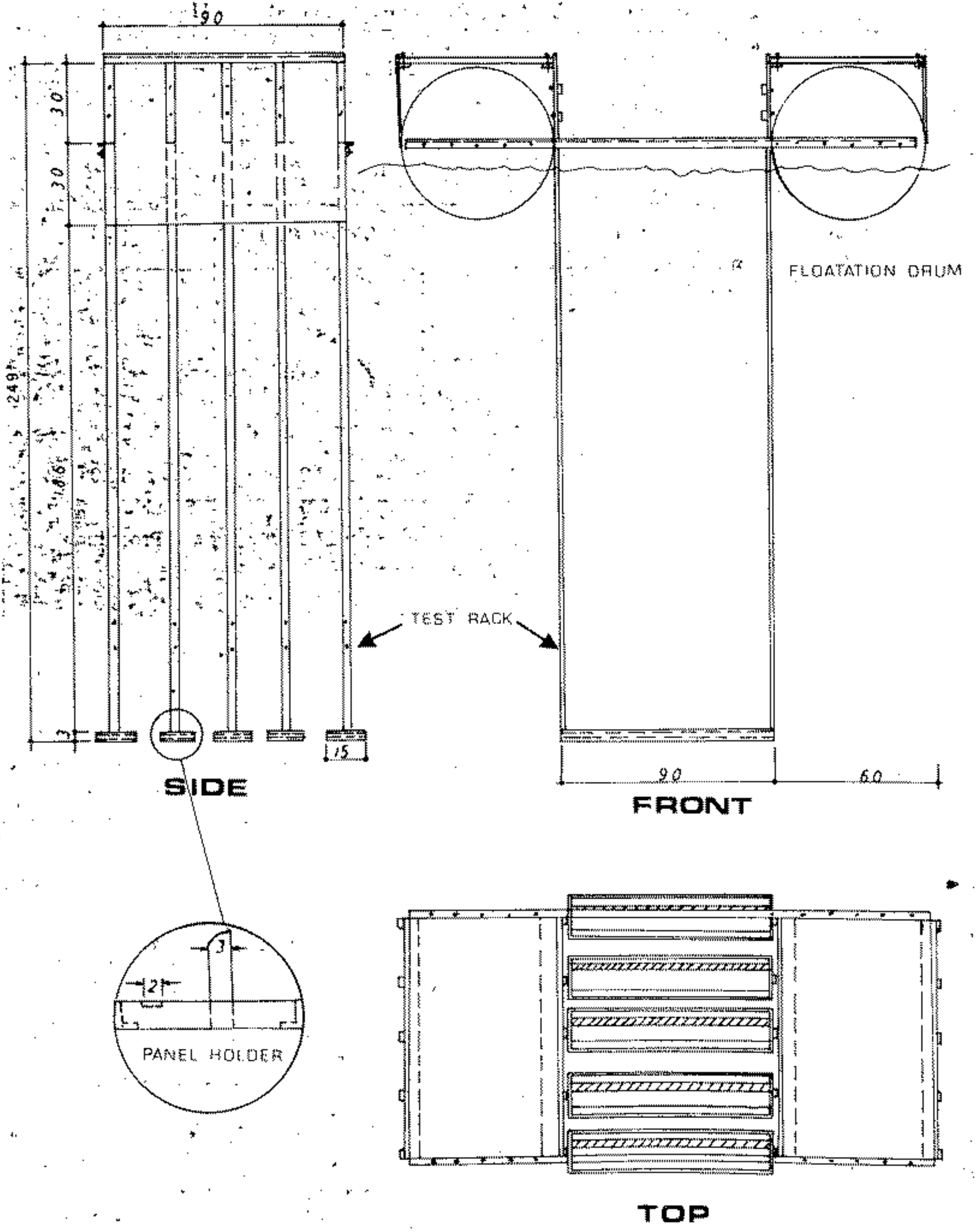

Fig. 2.—Testing station.

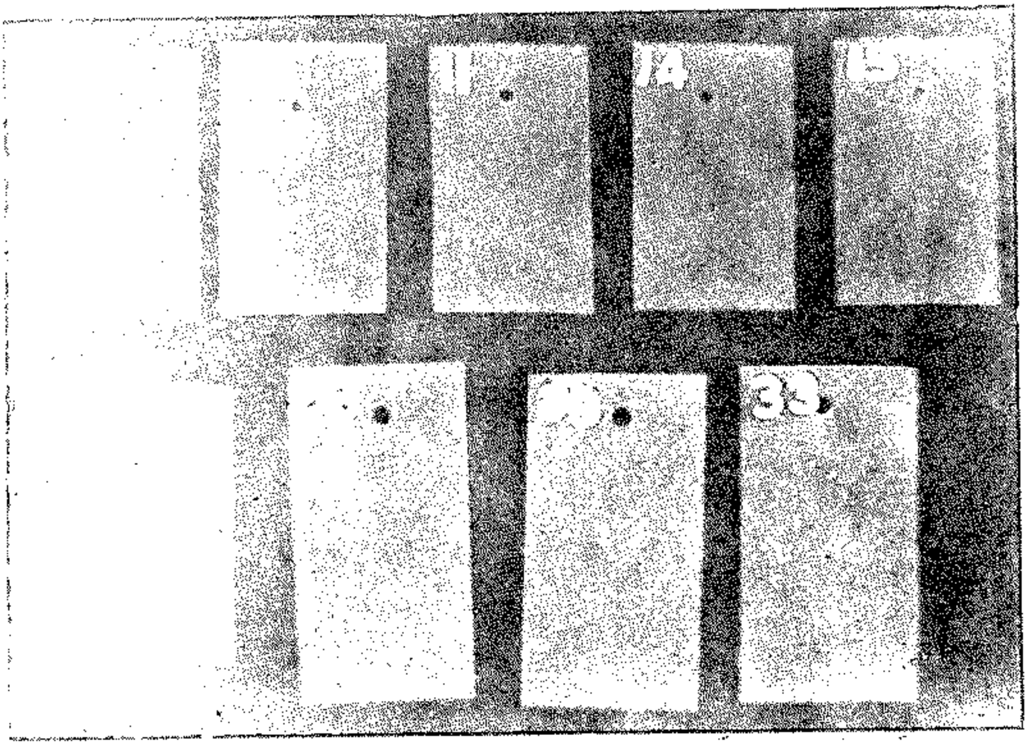

FIG. 3.—X-ray photographs of some test panels after completion of their test period.

3. ORGANOMETALLIC POISONS

Three organotin and one organolead compounds were used. These organometallic compounds are usually used in antifouling paint formulas. Table 3 summarizes the concentrations used.

4. CREOSOTES

The commercial product, brand name «Neverot», obtained from Texas Refineries Company, was used as is to impregnate the test panels. This composition contained 1.5 % of pentachlorophenol.

RESULTS

The degree of infestation was assessed as described in the previous section. Tables 4-7 describe the results of the borer count as well as the retention of the test panels to the toxic systems used. Some sample photographs of the test panels of each system are shown in figures 6-16.

DISCUSSION

The results of the treatment with inorganic systems clearly confirm earlier results (5) of other types of timber with regard to *L. tripunctata* and as expected to *B. gouldi*. However, in the system AB (tables 1 and 4), it was observed that mixing all three constituents resulted in a green precipitate, which is most likely the result of a reaction between potassium dichromate and arsenic trioxide. Therefore, this was used to the advantage of precipitating the toxic agent inside the wood fibers by using the «double treatment procedu-

TABLE 2

THE COMPOSITION OF THE PESTICIDAL SYSTEMS TESTED

SYSTEM			*Final Concentration (%)*
	COMPOSITION		
Code	*Chemical*	*Weight (g/l)*	
BA	Lindane	20.0	2.0
		100.0	10.0
BB	Chlordane	10.0	1.0
		100.0	10.0
BC	D.D.T. *	30.0	3.0

* As an emulssion in oil and water.

TABLE 3

THE COMPOSITION OF ORGANOMETALLIC SYSTEMS TESTED

SYSTEM			*Final Concentration (%)*
	COMPOSITION*		
Code	*Chemical*	*Weight (g/l)*	
CA	Bis-tributyltinoxide	15.0	1.5
		100.0	10.0
CB	Triphenyl-leadacetate	15.5	1.5
		100.0	10.0
CC	Bis-tributyltin-tetrachlorophthalate	15.0	1.5
		100.0	10.0
CD	Tributyltinfluoride	50.0	5.0

* The compounds tested were solubilized in 80:20, ethanol:methylenechloride.

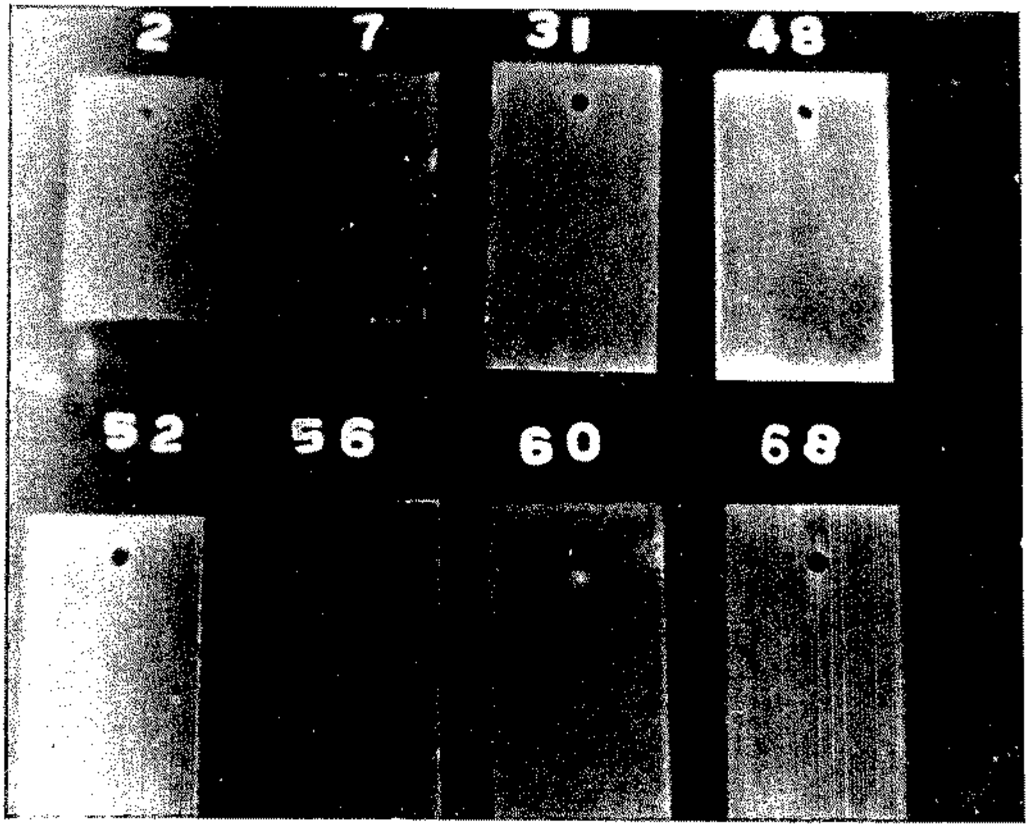

FIG. 4.—X-ray photographs of some test panel after completion of their test period.

re» (7), with the chromate-sulfate mixture first followed by immersion in the arsenic solution; which could account for the excellent protection afforded by the system AB (table 4).

As for the pesticidal systems (table 5), it is evident that they possess a selective activity against *L. tripunctata*, which is also in accord with tests on other types of timber (3). However, they were completely devoid of activity against *B. gouldi*.

The organometallic compounds used, are usually utilized in paint preparations as antifouling agents (6), except tributyltin oxide which was considered suitable additive to creosote in treating wood-pilings (4). The results in table 6 show that lower concentrations of the organometallic systems failed to afford protection against borers, while higher concentrations (10 %) of the organotin systems CA and CC was active against both species of borers up to 18-24 months, while the organolead compound, system CB, failed completely. As for tributyltin fluoride, system CD, it succeeded in affording complete protection against both boring and fouling organisms for at least three years. On the other hand, the commercial preparation «Neverot» which is intended originally to protect wooden poles, failed to protect local *Pinus brutia* more than six months.

It could, therefore, be concluded that both the inorganic system of copper sulfate-potassium dichromate followed by arsenic trioxide, system AB, and the organometallic system CD based on tributyltin fluoride afford complete protection of local *Pinus brutia* against the boring organisms *L. tripunctata* and *B. gouldi* in the northeastern shores of the Mediterranean port city of Lattakia.

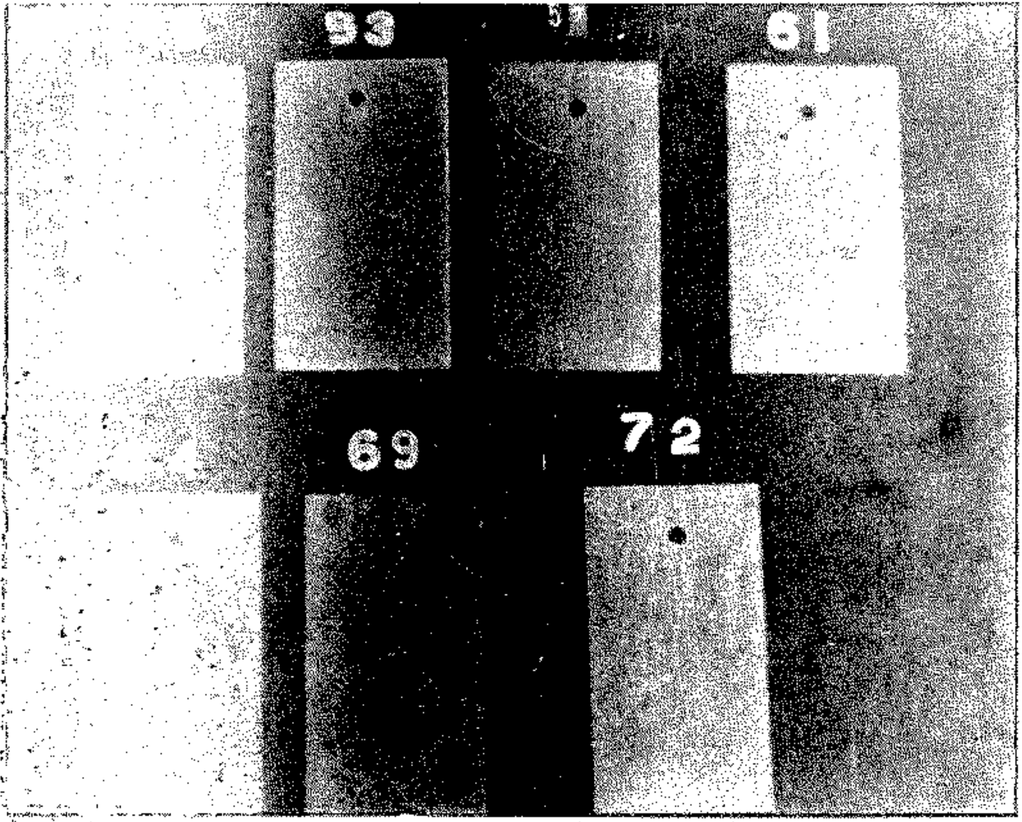

FIG. 5.—X-ray photographs of some test panels after completion of their test period.

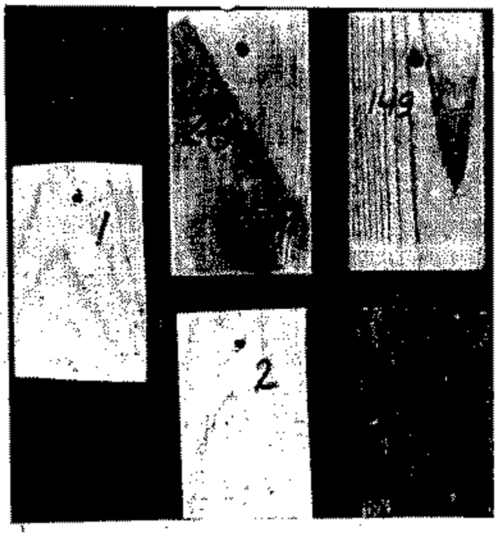

FIG. 6.—Representative test panels of system AA after completion of the test period.

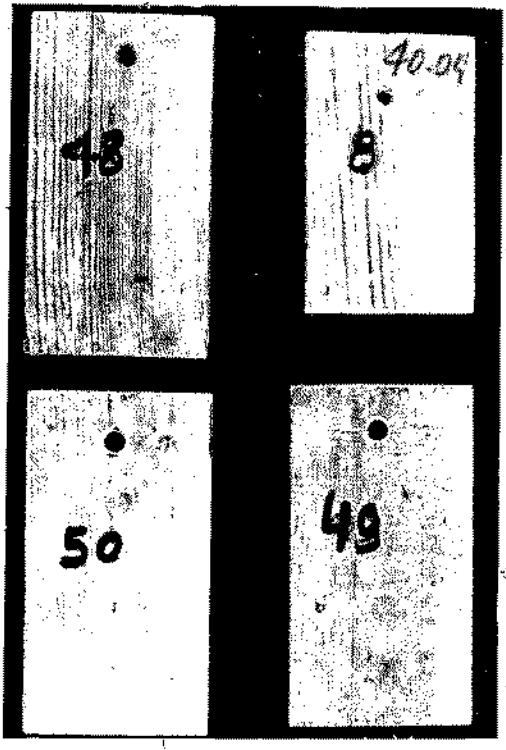

FIG. 7.—Representative test panels of system AB after completion of the test period.

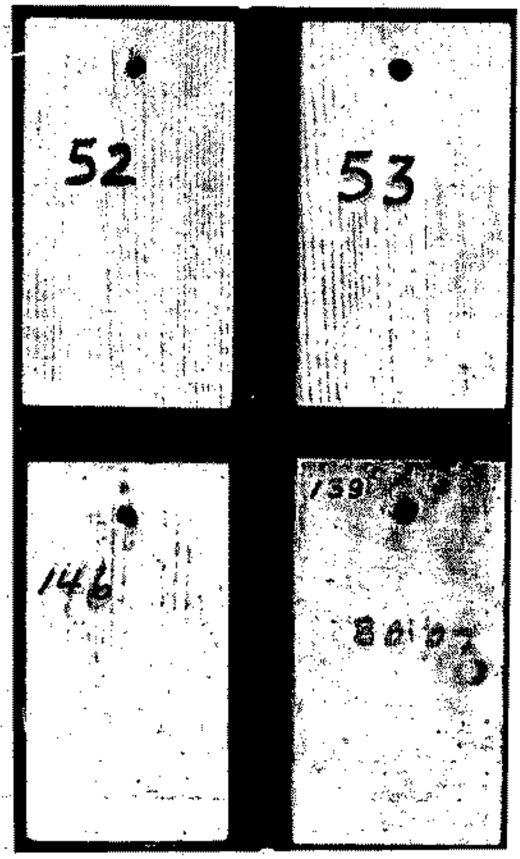

FIG. 8.—Representative test panels of system AC after completion of the test period.

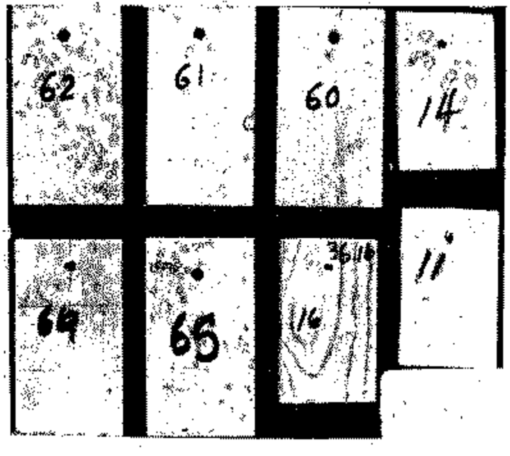

FIG. 9.—Representative test panels of system BA after completion of test period.

TABLE 4

THE RESULTS OF TESTING "PINUS BRUTIA" PANELS TREATED WITH INORGANIC SYSTEMS

Panel No.	SYSTEM		*Duration of test (mo)*	NUMBER OF ATTACKS		*Retention (kg/m³)*
	Code	*Conc. (%)*		B. gouldi	tripunctata	
1	AA	2.5	3	0	0	7.1
2			6	0	0	9.2
3			9	0	0	7.8
28			12	0	0	6.4
29			18	0	0	7.5
149			24	0	0	7.3
150			30	0	4	6.8
151			36	0	26	8.1
8	AB	10	3	0	0	27.7
48			6	0	0	30.9
49			9	0	0	31.4
50			12	0	0	28.1
140			18	0	0	33.0
141			24	0	0	28.7
142			30	0	0	26.9
143			36	0	0	30.3
52	AC	3	3	0	0	8.2
53			6	0	0	8.1
54			9	0	0	7.0
136			12	0	0	7.9
137			18	1	0	9.4
138			24	0	6	7.2
139			30	0	30	7.4
146			36	0	94	8.9

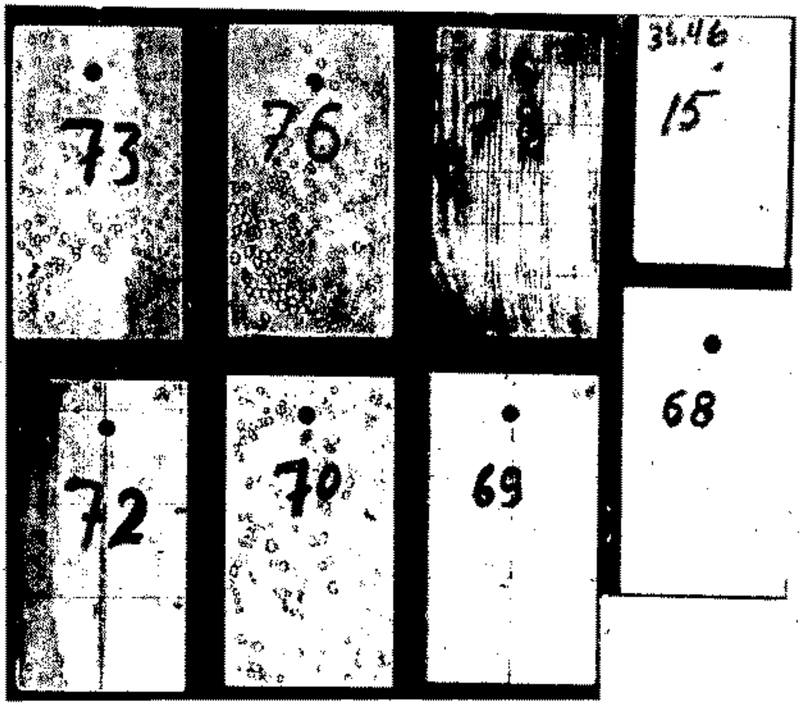

FIG. 10.—Representative test panels of system BB after completion of test period.

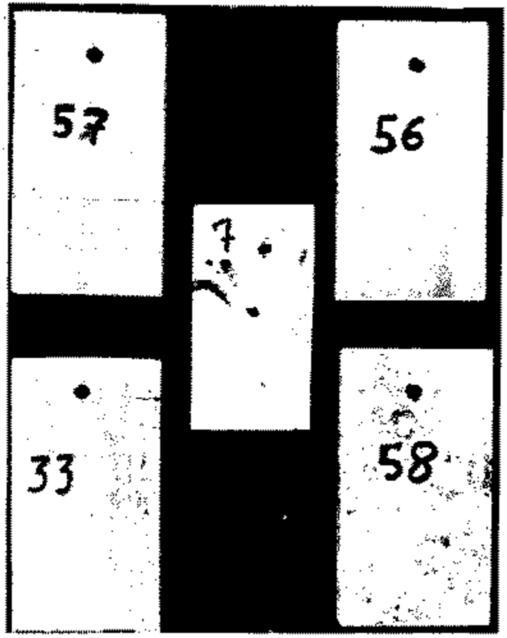

FIG. 11.—Representative test panels of system BC after completion of test period.

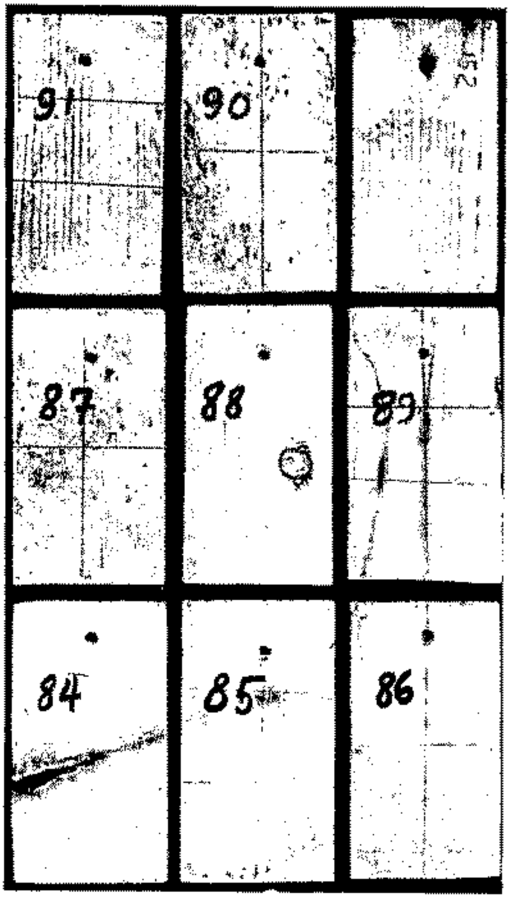

FIG. 12.—Representative test panels of system CA after completion of test period.

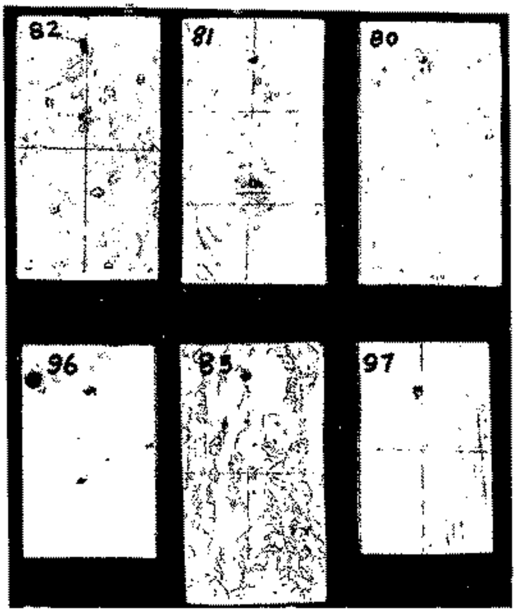

FIG. 13.—Representative test panels of system CB after completion of test period.

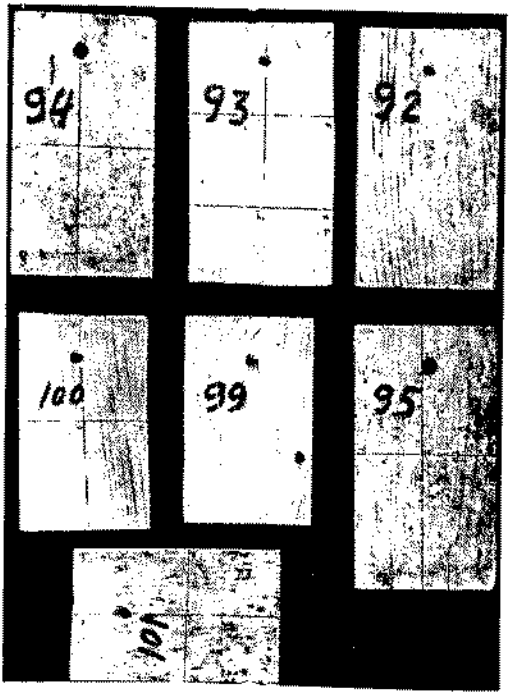

FIG. 14.—Representative test panels of system CC after completion of test period.

TABLE 5

THE RESULTS OF TESTING "PINUS BRUTIA" PANELS TREATED WITH PESTICIDAL SYSTEMS

Panel No.	SYSTEM		Duration of test (mo)	NUMBER OF ATTACKS		Retention (kg/m³)
	Code	Conc. (%)		B. gouldi	L. tripunctata	
11	BA	2	3	0	0	0.80
14		2	6	6	0	0.65
16		2	9	30	0	0.90
60		2	12	278	0	0.95
61		2	18	400	0	0.64
62		10	3	0	0	6.4
63		10	6	0	0	7.1
64		10	9	0	0	7.0
65		10	12	21	0	6.8
66		10	18	40	0	6.6
67		10	24	49	0	6.6
15	BB	1	3	1	0	0.4
68		1	6	24	0	0.4
69		1	9	139	0	0.45
70		1	12	200	6	0.35
71		1	18	350	20	0.42
72		10	3	0	0	2.1
73		10	6	0	0	4.2
74		10	9	0	0	3.4
75		10	12	4	0	3.4
76		10	18	38	0	2.9
77		10	24	90	0	2.8
78		10	30	178	0	4.0
7	BC	3	3	2	0	1.1
10		3	6	14	0	1.4
33		3	9	85	0	1.0
34		3	12	160	0	1.8
56		3	18	210	0	1.7
57		3	24	430	2	1.0
58		3	30	TNTC *	0	1.5
59		3	36	TNTC	5	0.9

* Too numerous to be counted.

TABLE 6
THE RESULTS OF TESTING "PINUS BRUTIA" PANELS TREATED WITH THE ORGANOMETALLIC SYSTEMS

Panel No.	SYSTEM		Duration of test (mo)	NUMBER OF ATTACKS		Retention (kg/m³)
	Code	Conc. (%)		B. gouldi	L. tripunctata	
84	CA	1.5	3	0	4	1.9
85		1.5	6	2	5	1.3
86		1.5	9	2	3	1.5
87		1.5	12	11	80	1.8
88		10.0	3	0	0	6.9
89		10.0	6	0	0	7.3
90		10.0	9	0	0	7.9
91		10.0	12	0	1	6.8
152		10.0	18	9	21	7.1
153		10.0	24	42	20	7.7
154		10.0	30	65	39	6.8
155		10.0	36	105	52	6.8
80	CB	1.5	3	71	69	1.6
81		1.5	6	89	62	1.4
82		1.5	9	183	126	1.4
83		1.5	12	241	139	1.9
96		10.0	6	0	0	7.4
97		10.0	12	5	3	9.2
92	CC	1.5	6	9	6	1.3
93		1.5	12	55	7	1.9
94		10.0	3	0	0	8.4
95		10.0	6	0	0	8.0
99		10.0	9	0	0	9.6
100		10.0	12	0	0	7.3
101		10.0	18	0	0	9.7
159		10.0	24	1	0	9.0
160		10.0	30	19	0	7.5
102	CD	5.0	3	0	0	5.1
103		5.0	6	0	0	5.5
105		5.0	9	0	0	6.4
156		5.0	12	0	0	4.6
157		5.0	18	0	0	5.1
183		5.0	24	0	0	6.1
184		5.0	30	0	0	5.8
185		5.0	36	0	0	5.8

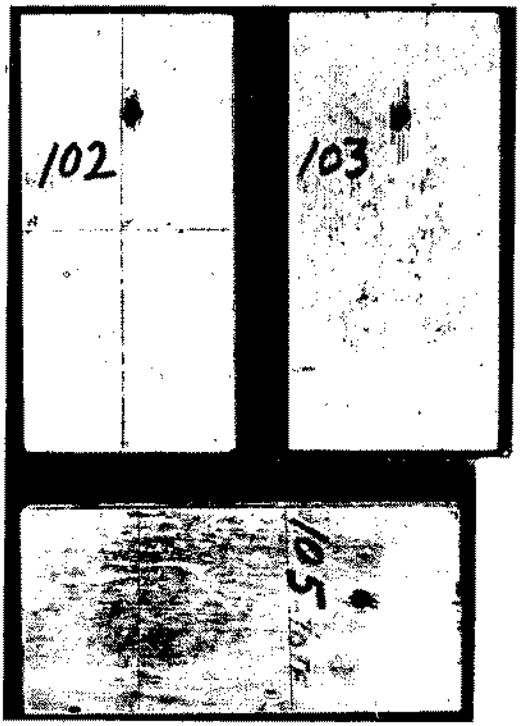

FIG. 15.—Representative test panels of system CD after completion of test period.

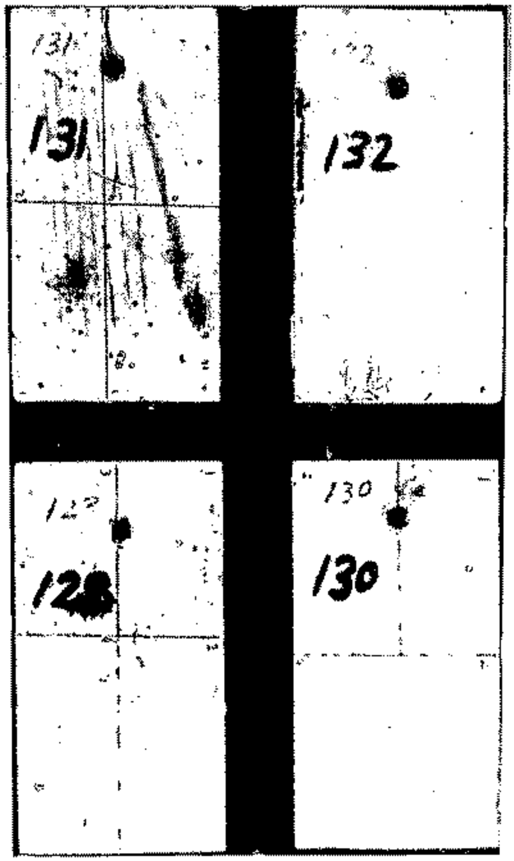

FIG. 16.—Representative test panels treated with "Neverot" creosote after completion of test period.

TABLE 7

THE RESULTS OF TESTING "PINUS BRUTIA" PANELS TREATED WITH THE CREOSOTE PREPARATION "NEVEROT"

Panel No.	*Concentration (%)*	*Duration of test (mo)*	NUMBER OF ATTACKS		*Retention (kg/m³)*
			B. gouldi	L. tripunctata	
128	1.5 *	3	0	0	3.2
129		6	0	0	3.4
130		9	9	0	2.9
131		12	26	9	3.2
132		18	129	16	3.5
133		24	400	39	2.7
134		30	TNTC **	80	2.9

* Pentachlorophenol.

** Too numerous to be counted.

ACKNOWLEDGEMENT

The author would like to thank the administration of the Center of Research and Scientific Studies for making this project possible and to Dr. A. W. Shaheed and Dr. A. H. Mansour for their continuous support.

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NOTES ON THE BIOLOGY OF THE SHIPFOULING GOOSENECK BARNACLE "CONCHODERMA AURITUM" LINNAEUS, 1776 (CIRRIPEDIA: LEPADOMORPHA)

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Denmark

INTRODUCTION

In recent years still more reports concerning fouling with the rabbit-eared gooseneck barnacle *Conchoderma auritum* Linnaeus, 1776, have appeared.

The most conspicuous feature of this species is the two earlike appendages on capitulum («the head») (Fig. 1). The shells are reduced and in adults, terga and carina may even be absent. Colour is variable from nearly white to dark brown. For detailed description see Nilsson-Cantell (21).

In the area off Namibia fishing vessels in particular meet a severe attack from this species.

Knowledge about *C. auritum* is' however, poor. The larvae and their development are yet undescribed and the description of the adults is almost solely in the morphological and zoogeographical field.

In this paper the geographical distribution of *C. auritum* and its choice of substrate is given. Moreover, some aspects from temporary studies of the eggs and larvae culturing, size at maturity and growth of this species are revealed.

MATERIAL

The material was collected from the seawater filters and the hull of the Spanish trawler «M/P Froxa», fishing in the area off Namibia (Fig. 2).

The owners and crew of «M/P Froxa» are warmly thanked for their cooperation.

RESULTS AND DISCUSSION

Distribution and choice of substrate

C. auritum is a cosmopolitan pelagic species (Fig. 3). The preferred non-human-made substrate is the balanomorphe cirriped *Coronula diadema* L., ectoparasitic on different species of whales.

On 97.8 % of *Coronula*, living in the skin of the humpback whale *Megaptera novae-*

Fig. 1.—*Conchoderma auritum*.

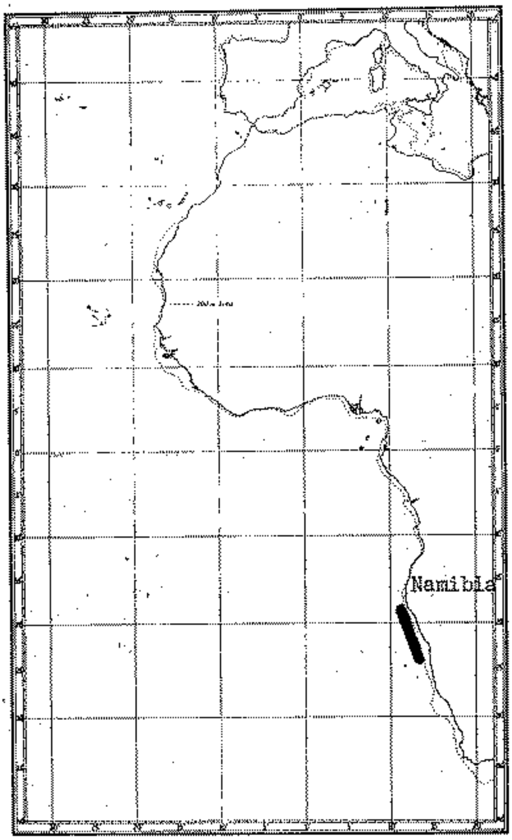

FIG. 2.—The fishing area off Namibia, where *Conchoderma auritum* was collected.

anglia from Antarctic, South Africa and the North Pacific, Clarke (4) found *C. auritum*. Other natural substrates are reported: teeth of the dolphin *Stenella frontalis* (3), the lower jaw of the common dolphin *Delphinus delphis* (24) and teeth and jaws of the sperm whale *Physeter catodon* (31).

So though Best (2) found *C. auritum* on the body skin of the elephant seal *Mirounga leonina*, this case seems to be the exception from the rule that *C. autitum* prefer a hard moving substrate usually near the surface (32).

During the four month stay onboard «Froxa» much drifting material was collected: big brown algae, feathers, pieces of polystyren, oil lumps, etc. These things often carried *Lepas* spp., but never *Conchoderma*, which was only found on the seawater filters and the ship hull.

GROWTH

When dealing with fouling organisms it is of great importance to find a method to determine the age and growth rate of the organisms, in order to tell when the organisms settled and in this way to get an indication of when the antifouling paint (A/F) had ceased being effective.

In order to find a reliable measurement of size, three variables were measured in the present study on preserved material:

1. Length of scutum — measured with an ocular micrometer.
2. Length of capitulum — measured with a vernier caliper as shown on Fig. 4.
3. Dry weight — weighed after 24 hours at 105° C.

No attempt was made to measure total size (capitulum + pedunculus), as the pedunculus is very contractible. Both the calcified scutum and the more soft capitulum appeared to be a good measurement of size. Both scutum and capitulum showed size allometry to dry weight with the allometric equations as shown on Figures 5 and 6 respectively.

Information on the growth rate of lepadomorphe cirripeds is scanty. In the known cases the given growth rates are minimum rates, as the exact settling time is unknown. Some information about the growth rate was collected from «Froxa's» seawater filters with no A/F paint applied. One filter (20 cm × × 30 cm) was carefully examined after 30 days exposure to the seawater.

Of fouling cirripeds some tiny *Balanus amphitrite*, eight individuals of *Lepas fascicularis* and 87 individuals of *C. auritum* were found. Figure 7 shows the size distribution of the latter species.

On the assumption that the biggest individuals settled right at the start of exposure it can be inferred that these individuals are 30 days old. The mean capitulum length of the biggest individuals was measured to 20.4 mm (SD = 0.9, n = 5), which gives a growth rate of 0.7 mm/day during the first month of living.

Evans (10) found lower growth rates (0.5 mm/day) for *Lepas anatifera* and *Lepas hilii* grown in water ranging from 24.2°-26.1° C. For *Conchoderma virgatum* Darwin (8) found

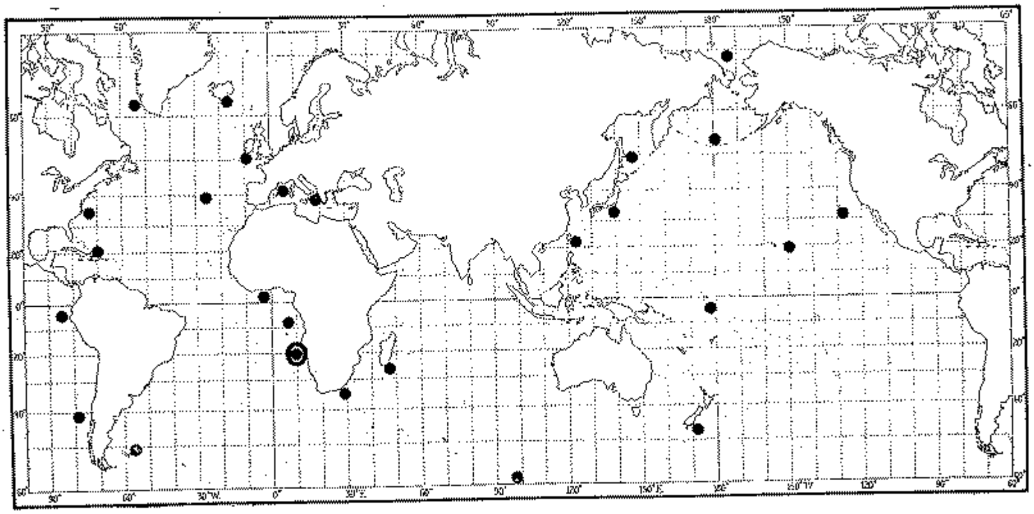

FIG. 3.—Distribution of *Conchoderma auritum*. Ref.: 3, 4, 12, 13, 22, 23, 24, 28, 31, 33. Present study: ○

FIG. 4.—*Conchoderma auritum*. Length of capitulum was measured as shown with a vernier caliper.

that this species grew to a capitulum length of 14 mm during 33 days near Galapagos, corresponding to 0.4 mm/day. So compared with the three lepadomorphe species mentioned, the growth rate for *C. auritum*, at least during the first month of living, is higher, though grown in water ranging from 16°-19° C.

Mean capitulum length of the biggest individuals at maximum 150 days of age was 33.6 mm (SD = 1.5, n = 5), so the high growth rate during the first month of living is not maintained, but is probably lowered after maturity as a consequence of metabolic changes.

FECUNDITY

The fertilized eggs (the embryos) are glued together and form in the mantle cavity the two double and pink egglamellae. The living eggs were counted by spreading the lamellae carefully on millimeter paper. The egg size was measured with an ocular micrometer.

To ascertain the kind of relationship existing between production of embryos and size of the animal, the egglamellae and the individuals from which the lamellae were dissected, were dried (105° C/24 h) and weighed.

The egg size is within the same range as other known shipfouling gooseneck barnacles: *Lepas anatifera. Lepas pectinata, Lepas fascicularis and Conchoderma virgatum* (16), while the egg number is factor hundred times higher (figure 8 and table 1). There was a strong positive correlation (r = 0.89) between dry weight of animal without embryos and dry weight of embryos (Fig. 9), which means that bigger animals have a bigger production of eggs. For *Scalpellum scalpellum*, KAUFMAN (14) did not find any relationship between egg number and size of the animal.

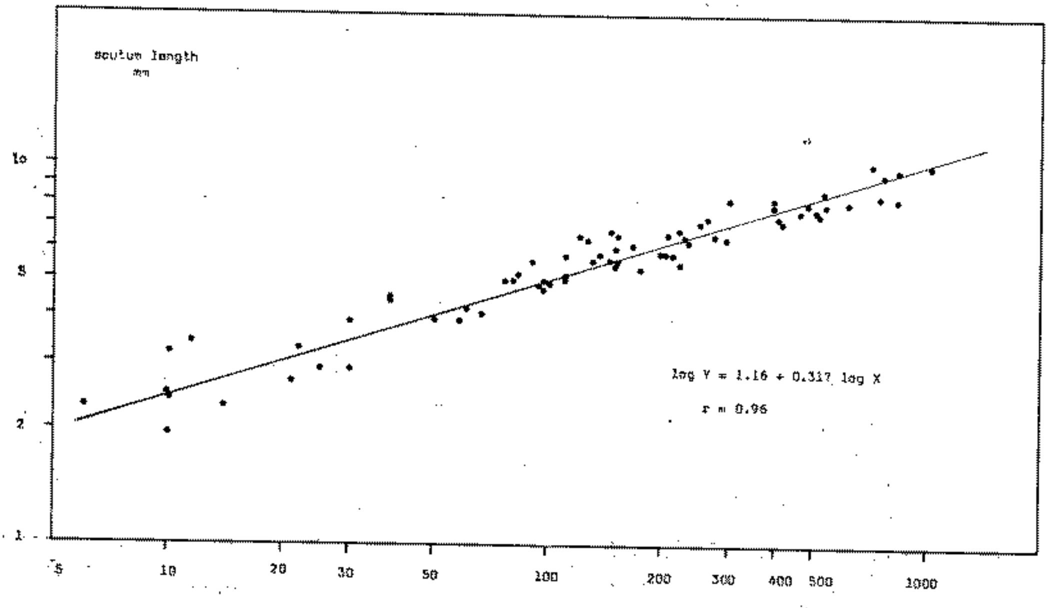

FIG. 5.—Scutum length related to total dryweight.

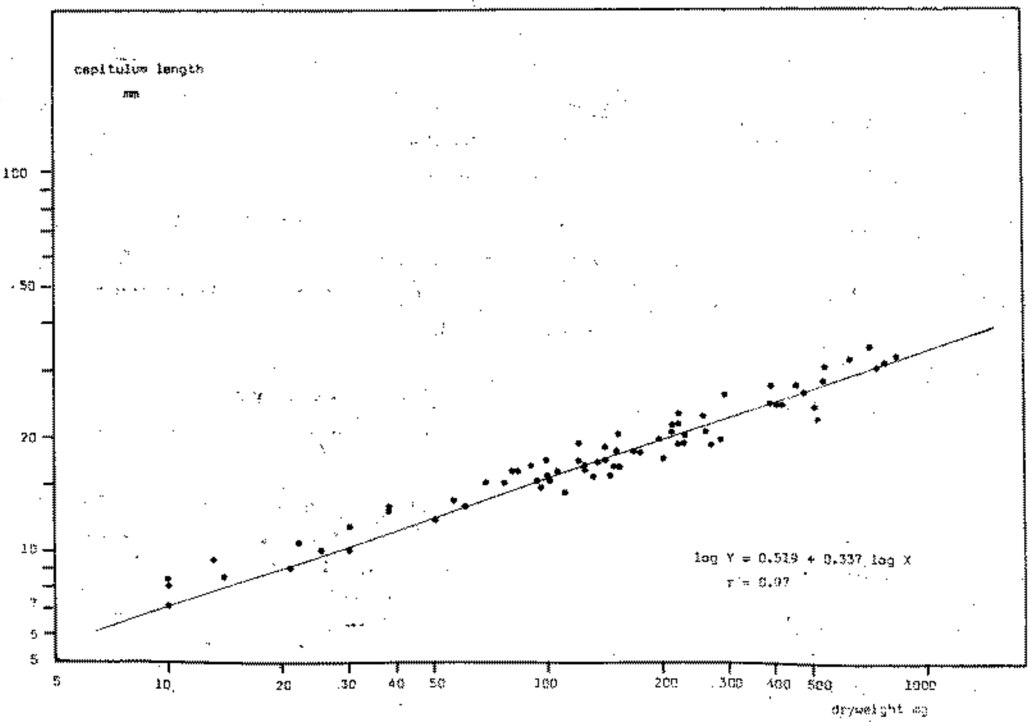

FIG. 6.—Capitulum length related to total dryweight.

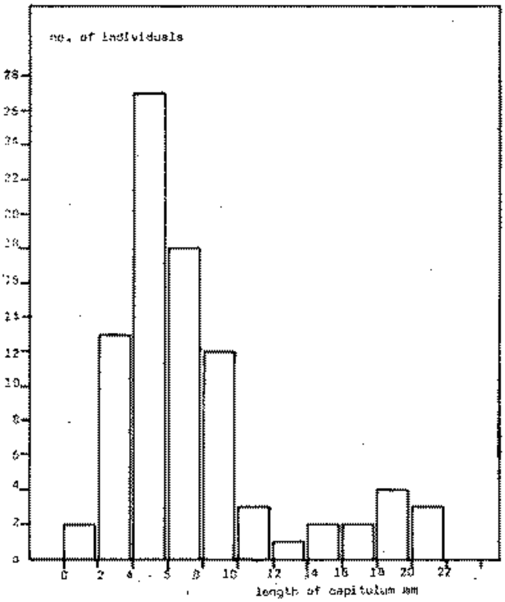

FIG. 7.—Size distribution of all individuals found on seawater filter after 30 days of exposure.

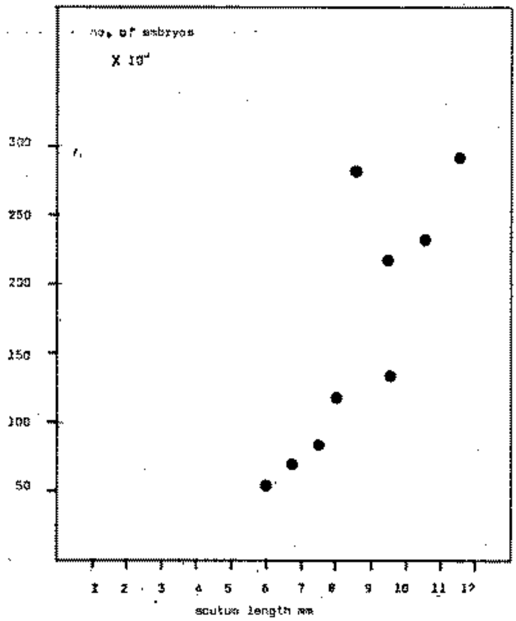

FIG. 8.—Number of embryos related to scutum length.

TABLE 1

Species	Egg length (mm)	Egg number	
Lepas anatifera	0.189	1,400	KRÜGER (16).
Lepas pectinata	0.17	1,100	
Lepas fascicularis	0.26	1,900	Egg number determined by volume.
Conchoderma virgatum	0.186	1,700	
Conchoderma auritum	0.161	164,000	Present author.

MATURATION

The formation of egglamellae is a safe indication that the animal has reached maturity. About 400 individuals in different size groups collected from May to October were examined for the presence of egglamellae.

Five individuals from the 30 days exposed seawater filter carried egglamellae. So it can be inferred that *C. auritum* is able to reach maturity in less than 30 days. *Lepas anatifera* and *Lepas hilii* need between 30-50 days to reach maturity (10, 26), which is the same order of magnitude *Balanus amphitrite* need before it carries embryos in Hawaian waters (9).

In the present study the smallest mature individuals were found in the group with a scutum length between 4-5 mm, but it can be stated that it is not normal for *C. auritum* to carry embryos before it reaches a scutum length greater than 77 mm. In the part of the population with a scutum length greater than 7 mm, 72 % of the individuals had embryos (Figure 10).

At the present moment the significance of this rather high number of pregnant individuals cannot be determined, as knowledge of the embryonic and larval development is yet very sparse. However, the high number of pregnant animals collected during a time span of four months and the comparable high number of eggs of this species could indicate a high reproductive potential — one factor of importance for the success of a fouling organism.

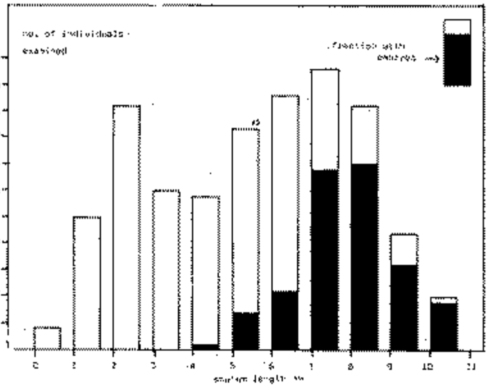

FIG. 10.—The size distribution of the total number of individuals examined for presence of egglamellae (embryos).

CULTURING OF LARVAE

The use of different species of barnacle cyprids has been common in screening tests for the toxins used in A/F paints (6, 7, 9, 29, 30). Literature about culturing lepadomorphe larvae, however, is poor. LEWIS (18) reared *Pollicipes polymerus* to settling stage and so did KAUFMANN (14) with *Scalpellum scalpellum.*

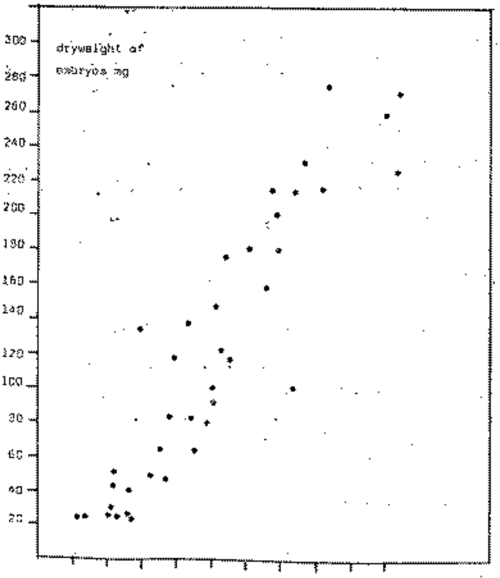

FIG. 9.—Dryweight of embryos (egglamellae) related to dryweight of animal after removal of egglamellae.

In an attempt to rear the larvae of *C. auritum,* egglamellae from adult individuals with active cirri movements were carefully removed and incubated in 500 ml beakers containing 0.6 μm filtered seawater to which was added 0.1 ml Crystamycin/l (29). Crystamycin is a mixture of streptomycin and penicillin. The lamellae were kept at the same temperature as the ambient seawater (16°-19°), and continuously provided with a gentle flow of air.

The embryonic development was not followed in detail, except that the prevailing embryonic stage was noted at the start of the experiment, according to BARNES and BARNES (1). The nauplius I appeared 3-6 days after the lamellae had been incubated, and upon hatching 2,000-3,000 larvae were transplanted to Perspex tubes (vol. 365 ml), provided in the lower end with a 225 μm nylon net. The Perspex tubes were kept floating in the aquarium where 0.1 ml Crystamycin was added per liter of seawater. The water (16°-19° C) was changed twice a day.

A sample of the larvae was examined every day for activity and to ascertain that the guts were full.

Unfortunately the nauplii could not be reared to settling stage, but died after 3 weeks, probably due to heavy diatom build up in the aquarium.

During this study about four hundred mature individuals have been examined. No further larval stages developed after nauplius I were found in the mantle cavity, and in the few cases found they were always mixed with late embryonic stages: Groom's embryonic stages F-G-H (1). So the result of the present examination does not confirm the assumption of WOLFF (31) and NILSSON-CANTELL (21) that the nauplii are developed in the mantle cavity and the first free stage is the cypris. Larval development in the mantle cavity seems more common in deep sea species (20) and in species with fewer eggs.

TABLE 2

Time (h)	*No. of cyprids*	*No. of metamorphosed individuals*
0	32	0
6	32	0
12	31	1
18	30	1
24	29	1
30	26	3
36	21	5
42	12	8
48	9	3
54	6	3
60	6	0
96	6	0
		(No activity)

Mean	37.8
SD	11.1

Duration of metamorphosis:

Balanus crenatus, 20 h (15).
Balanus improvisus, 20-24 h (17).
Balanus balanoides, 36 h (5).
Balanus balanoides, 20 h (15).
Balanus balanoides, 10-12 h (17).

METAMORPHOSIS

One of the most critical periods in the life of any cirriped is the time of settling, when the cyprid larva choose substrate and start to metamorphosize.

Metamorphosis was followed by selecting 32 cyprid larvae still in the ambulatory phase and therefore not yet permanently glued to the substrate. The larvae were examined every 6 hours until the formation of pedunculus could be observed, which was considered to be the indication that metamorphosis had taken place.

The results are shown in table 2.

As the table shows, there is some difference in the duration of metamorphosis between species. Whether the difference is real or due to difference in methods is difficult to say, but 37.8 h for *C. auritum* seems rather slow.

SUMMARY

C. auritum is a cosmopolitan that prefers hard substrates in motion.

The results of this preliminary study show that *C. auritum* needs less than 30 days to reach maturity, that the number of eggs is far greater than known for other fouling lepadomorphe cirripeds. Further, that bigger animals have more embryos.

Though not yet described from plancton, there is no indication that the nauplii are developed in the mantle cavity as previously assumed.

Compared with other fouling cirripeds, the metamorphosis of *C. auritum* is rather slow, so it is likely that this species successful invasion of A/F applied ship hulls must be ascribed to other reasons than a shorter stay in the laminar layer, where the concentration of the toxin is thought to be greatest (11).

It was found that both scutum length and capitulum length were good measurement for size.

A rough estimate of the growth rate during the first living month showed a value of 0.7 mm/day; a value slightly greater than that found for other fouling lepadomorphe cirripeds.

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MACROFOULING OF A LAGOON IN THE PO RIVER DELTA

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INTRODUCTION

A large electric power station is currently being built between the river Po (Pila branch) and the «Sacca del Canarin» (Fig. 1), a brackish lagoon delimited by sand dunes on the seaward side, by artificial embankments on the landward side and generally encircled by the reeds *(Phragmitetum)*. It is proposed that the cooling water for the power station will be drawn from either the river Po or from the brackish Sacca del Canarin.

The macrobenthos settling on asbestos panels and various other hard substrata in the lagoon Sacca del Canarin was investigated over two years in order to determine which fouling organisms were likely to be present in the conduits of the power station and to evaluate possible changes in the benthic communities living in this brackish environment as a result of its operation.

The lagoon is very shallow (less than 1.5 m) and influenced by both seawater and freshwater (from the river Po) entering at various sites. The salinity of the lagoon varies considerably but is generally low and, sometimes in the northern part, does not exceed 1·5 $^0/_{00}$; temperature and nutrient levels can also vary considerably.

At the present time there are many investigations in progress on the environment of the lagoons in the river Po delta but the results have not yet been published. Some data is available in Parisi (1973 *a, b*).

MATERIALS AND METHODS

Asbestos cement panels (200 × 300 × 3 mm) were immersed over two years between January 1977 and December 1978 in several stations representing the main environmental conditions. The panels were exposed for 1, 3, 6, 9 and 12 month periods at four stations (A, B, C, D); during the second year three additional stations (H, L, S) were investigated. One of the latter stations was sited in a neighbouring lagoon (Sacca di Scardovari) to act as a control, especially for future studies. Samples were also regularly collected from natural substrata at twelve stations distributed around the borders of the lagoon in each season and these compared with organisms settled on the plates.

This paper deals only with the fouling organisms collected on the panels.

Settlement of fouling organisms was estimated by weight (wet weight of the whole community present on the panel), by counting, when possible, individuals or colonies, and by the use of cover indices (5 = more than 75 % of the surface covered by an organism or a group; 4 = from 50 to 75 %; 3 = 25 to 50 %; 2 = 5 to 25 %; 1 = less than 5 %; + = negligible settlement). The data on percentage cover by each of the main fouling groups is presented in Figures 2 and 3.

STATIONS

Station A is located near reeds and influenced by seawater, and freshwater coming from the south.

Station B is situated in the middle of the

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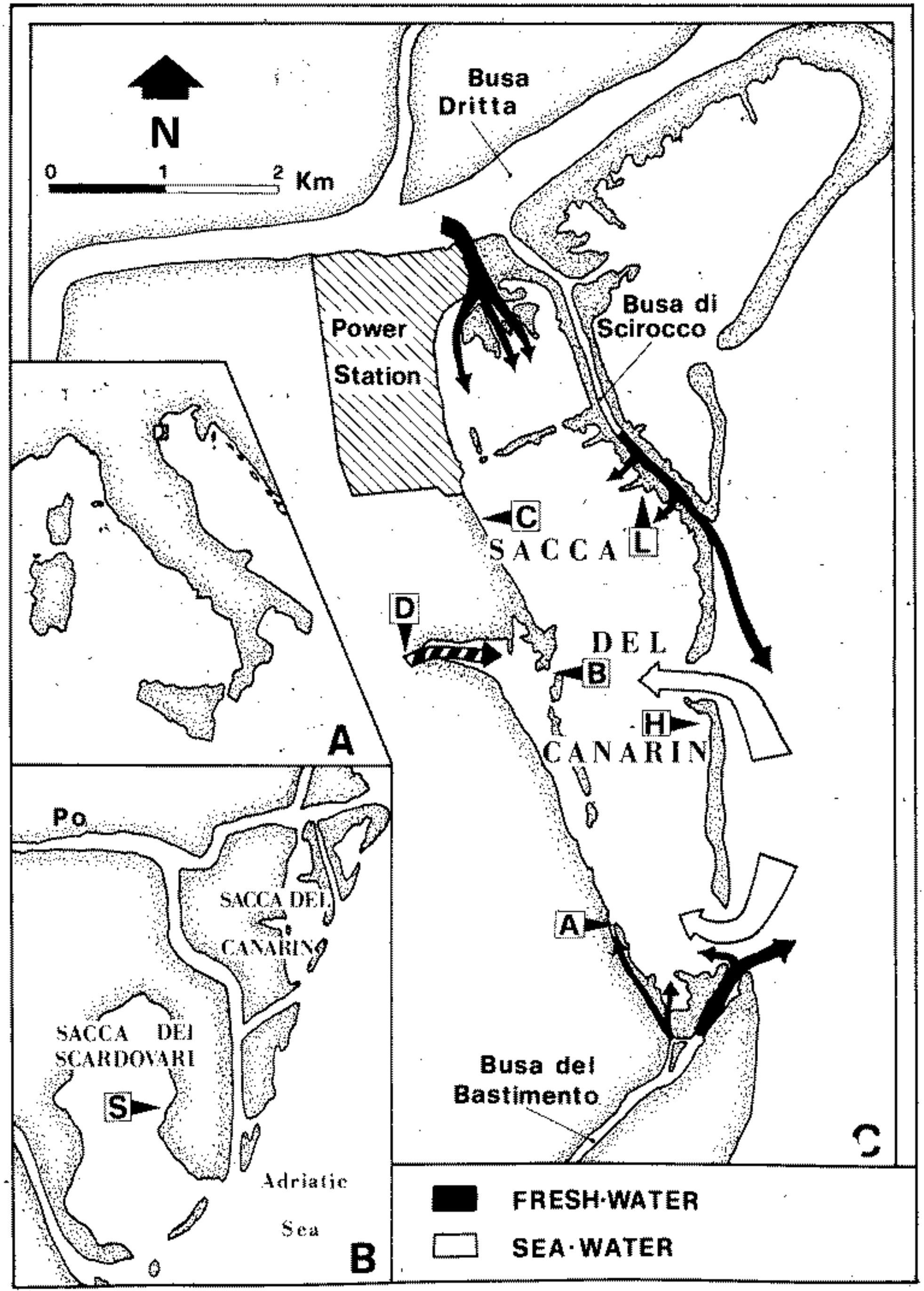

Fig. 1.—Map of the lagoons. A: the small square indicates the river Po Delta. B: the lagoons "Sacca del Canarin and "Sacca dei Scardovari" situated south of the Pila branch of the river Po. C: stations for immersion of panels in the Sacca del Canarin. The arrows shows the main incoming of freshwater and of sea water.

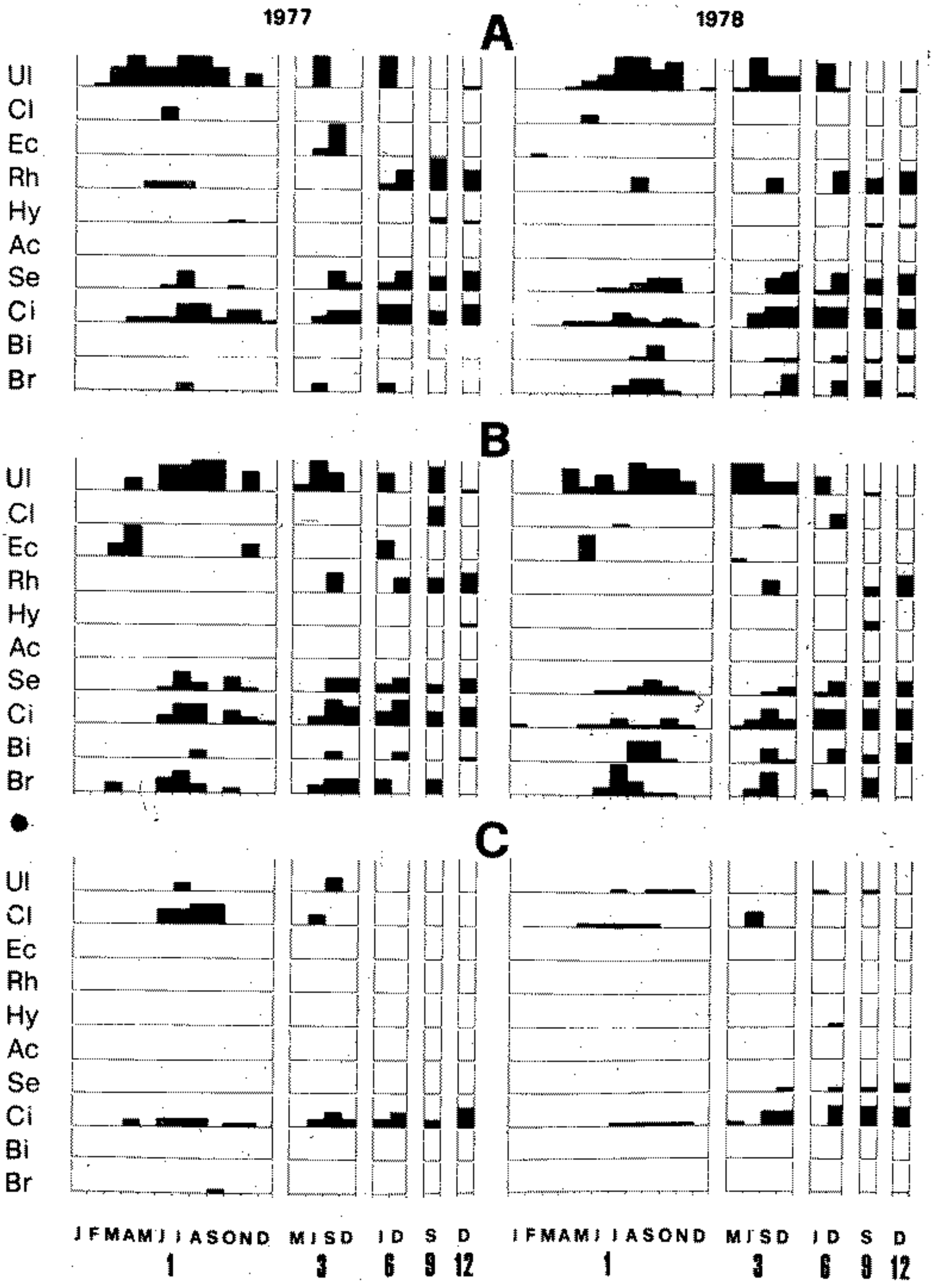

FIG. 2.—Settlement, as percentage of surface covered by each group, on panels exposed at stations A, B, C for 1, 3, 6, 9, 12 months in 1977 and 1978.

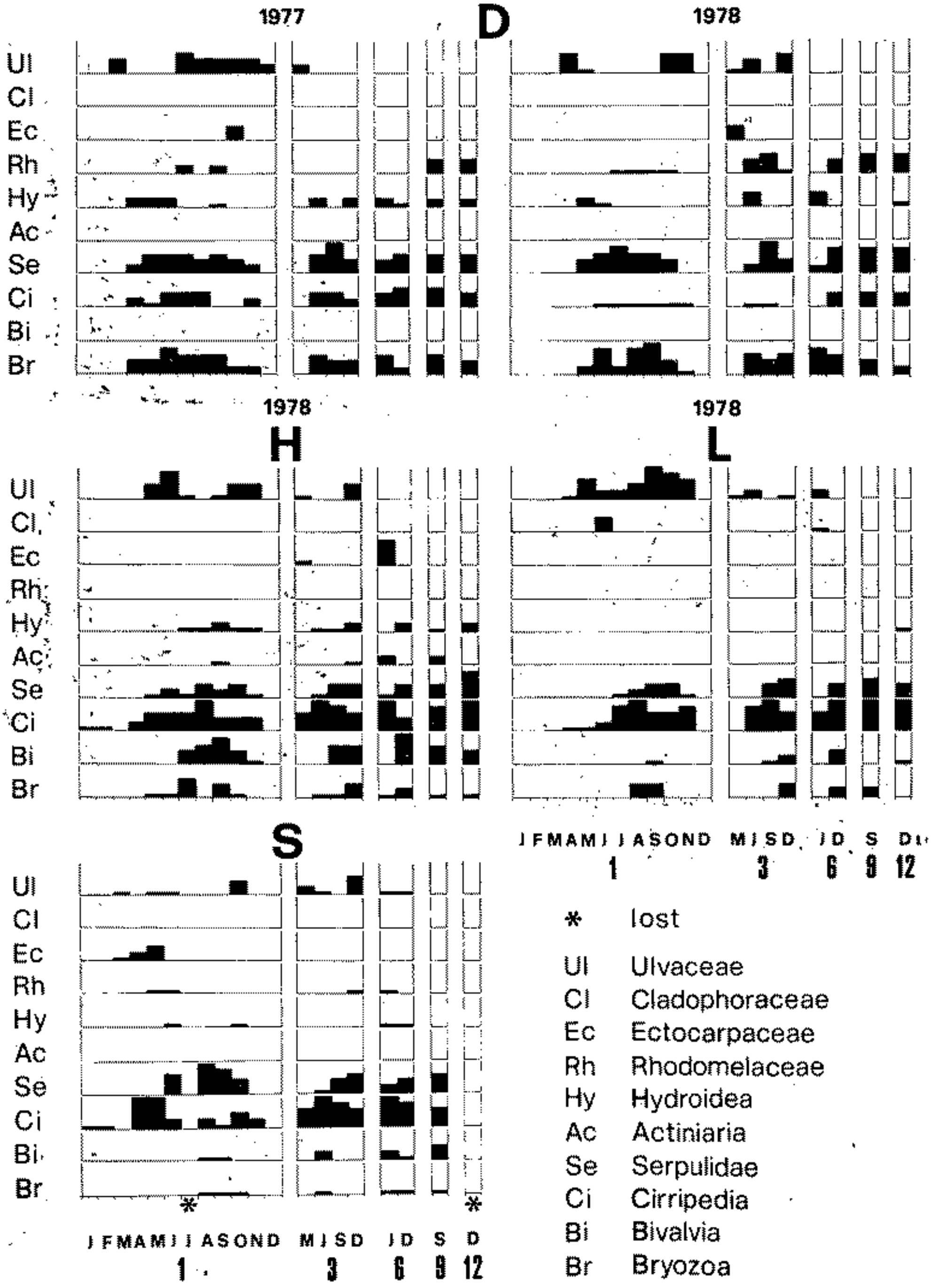

FIG. 3.—Settlement, as percentage of surface covered by each group, on panels exposed at station D for 1, 3, 6, 9, 12 months in 1977 and 1978 and at stations H, L and S only during 1978.

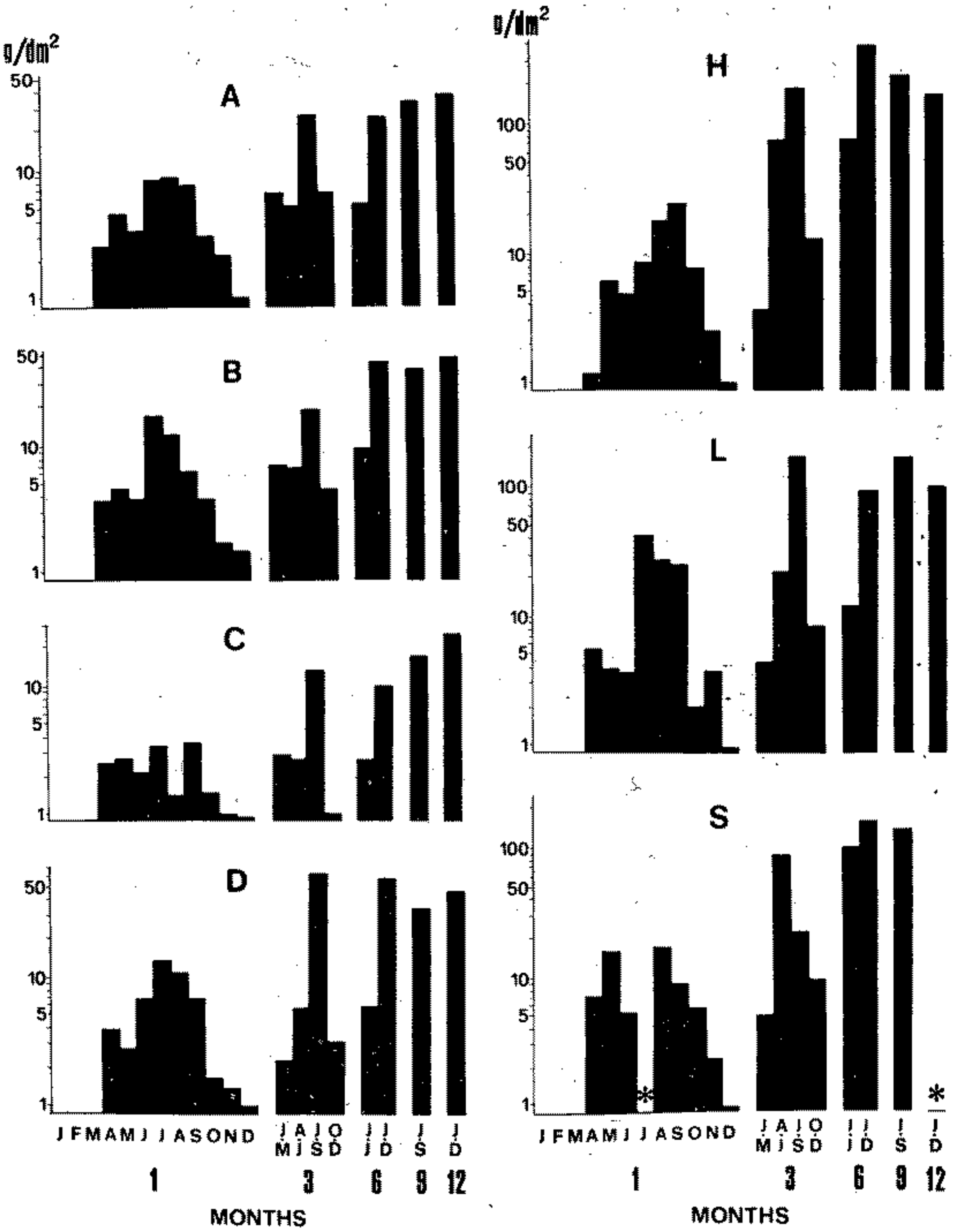

FIG. 4.—Wet weights (g/dm2) of fouling settled on 1, 3, 6, 9, 12 months plates immersed at seven stations during 1978. The asterisks means lost panels.

TABLE 1

LIST OF ANIMAL SPECIES RECORDED AT DIFFERENT STATIONS

	A	*B*	*C*	*D*	*H*	*L*	*S*
CNIDARIA							
HYDROIDEA							
Cordilophora caspia (Pallas)	—		—	—		—	
Obelia bidentata (Clarke)					—		—
Laomedea calceolifera? (Hincks)		—			—		
Ventromma halecioides (Alder)				—			—
ACTINIARIA							
Paranemonia cinerea (Contarini)					—		
PLATHELMINTHES							
POLYCLADIDA							
Stylochus mediterraneus? (Galleni)	—	—		—	—	—	—
ANNELIDA							
POLYCHAETA							
Neanthes succinea (Leuckart)	—	—		—	—	—	—
Polydora ciliata (Johnston)					—		—
Ficopomatus enigmaticus (Faûvel)	—	—	—	—	—	—	—
ARTHROPODA							
CIRRIPEDIA							
Balanus improvisus Darwin	—	—	—	—	—	—	—
Balanus eburneus Gould	—	—		—	—		—
Balanus amphitrite Darwin					—		
AMPHIPODA							
Leptocheirus pilosus Zaddach	—	—	—	—	—	—	—
Corophium acherusicum Costa			—	—			—
Corophium insidiosum Crawford	—	—	—		—		
Corophium orientale Schellemberg			—				

TABLE 1 *(Continued.)*

	A	*B*	*C*	*D*	*H*	*L*	*S*
Echinogammarus sp.p.	—		—			—	
Gammarus aequicauda (Martynov)				—			
Gammarus crinicornis Stock	—	—					—
Melita palmata (Montagu)							—
Jassa sp.			—				
TANAIDACEA							
Heterotanais gurneyi Norman	—	—	—			—	—
ISOPODA							
Sphaeroma hoockeri Leach	—			—	—	—	—
DIPTERA							
Chironomidae (larvae)			—			—	
MOLLUSCA							
GASTROPODA							
Hydrobia ventrosa (Montagu)				—			
BIVALVIA							
Scapharca inaequivalvis (Bruguiere)					—		
Mytilus galloprovincialis Lamarck					—		—
Mytilaster minimus (Poli)					—		—
Crassostrea gigas (Thundberg) (= *C. angulata* Lam.)	—	—			—	—	—
BRYOZOA							
CHEILOSTOMATA							
Conopeum seurati (Canu)	—	—		—	—	—	—
CTENOSTOMATA							
Bowerbankia gracilis (Leidy)		—					
Victorellidae	—	—		—	—	—	
ENTOPROCTA							
Barentsia benedeni (Foettinger)		—					

TAB

SETTLEMENT OF BARNAC

							1 MONTH	
		J	*F*	*M*	*A*	*M*	*J*	*J*
A	*B. improvisus*					+	1	17
	B. eburneus							
	B. sp.				+	1	4	14
B	*B. improvisus*						+	56
	B. eburneus							
	B. sp.						5	3
C	*B. improvisus*						1	1
	B. eburneus							
	B. sp.				1		5	8
D	*B. improvisus*						15	3
	B. eburneus							
	B. sp.				+		1	+

western border of the lagoon and is less influenced by freshwater than station A.

Station C is strongly influenced by freshwater, as it is positioned on the western border in the main flow of the river Po.

Station D is located in a small canal at the end of a creek and periodically receives water which is pumped from the land; the environment is, therefore, both sheltered and very rich in nutrients.

Station H is situated on the eastern border near the main seawater entrance to the lagoon, and is the most marine site under investigation. No reed is present. At this site panels are also submitted to strong tidal currents.

Station L is sited in the north eastern part of the lagoon, near a large reeds and is influenced by both freshwater and seawater.

Station S is sited in another lagoon, «Sacca di Scardovari», which has water of higher salinity than that recorded in the Sacca del Canarin. The water is also deeper and the fouling community has a good diversity of species; mussels are very common here while in the Sacca del Canarin they are rare.

RESULTS

LIST OF SPECIES

The macrobenthic species recorded on the panels were identical to those collected on the natural hard substrata. Approximately thirty species of animals were identified, half of these in quite large quantities. The main algae present were species of the genera *Enteromorpha, Ulva, Cladophora, Polysiphonia* and *Ectocarpus;* in particular the following species have been identified: *Enteromorpha jugoslavica* (Bliding), *E. kylinii* Bliding, *E. compressa* (L.) Greville, *E. flexuosa* (Wulfen)

L E 2

LES DURING 1977 (N°/dm²)

					3 MONTHS				6 M		9 M	12 M
A	S	O	N	D	J-M	A-J	J-S	O-D	J-J	J-D	J-S	J-D
23	+	2				1	34	4	3	21	5	4
7	8	3	54	+		+	5	35	2	23	7	5
1		6	1				67	12	1	88	11	23
							16			12	4	5
5		9	36	1		1	11	34	2	15	7	15
+			+			+	2	7	1	7	1	8
+		5	2			3	2	7	2	61	6	13
1						2	1		1	2	2	1
							3			6	4	3
1			1			1	2	+	+	2	1	1

J. Agardh, *Ulva curvata* De Toni, *Polysiphonia montaguei* Zanardini and *Ectocarpus siliculosus* (Dillw.) Lyngbye. The main animal species collected on the panels immersed at the different stations are recorded in Table 1. The smallest diversity in species composition occurred at Station C, the greatest at Station H. In general the fouling community recorded especially on the monthly plates had a poor species composition.

In the Sacca del Canarin the main fouling organisms recorded, in order of importance, were: *Ficopomatus (= Mercierella) enigmaticus* (Fauvel), *Balanus improvisus* Darwin, *B. eburneus* Gould, *Crassostrea gigas* (Thunberg), *Echinogammarus* spp, *Leptocheirus pilosus* Zaddach, *Conopeum seurati* (Canu) and *Bowerbankia gracilis* (Leidy).

At Station S, situated in the Sacca di Scardovari, the main fouling organisms were: *Mytilus galloprovincialis* Lamark, *C. gigas*, *B. eburneus*, *B. improvisus*, *Mytilaster minimus* (Poli) and *F. enigmaticus*.

SETTLEMENT PERIODS

The pattern of settlement, in terms of percentage surface cover, for the main groups of fouling organisms on panels immersed for 1, 3, 6, 9 and 12 months at the seven stations is presented in Figures 2 and 3. For Stations A, B, C and D, data over a two year period of investigation is presented.

Settlement of marine organisms was generally heaviest during the summer and very light in winter. From December to March only some algae and one Barnacle *(B. improvisus)* succeeded in settling.

Tables 2, 3, 4 and 5 record some settlement densites (No. of individuals/dm²) for the most important fouling species of barnacles, serpulids and molluscs.

TAB

SETTLEMENT OF BARNAC

							1 MONTH	
		J	*F*	*M*	*A*	*M*	*J*	*J*
A	*B. improvisus*					+	+	16
	B. eburneus							
	B. sp.				+	+	1	4
B	*B. improvisus*					+		8
	B. eburneus						+	
	B. sp.	1					1	
C	*B. improvisus*							4
	B. eburneus							
	B. sp.							4
D	*B. improvisus*						2	1
	B. eburneus							+
	B. sp.						+	
H	*B. improvisus*					127	15	322
	B. eburneus							+
	B. sp.	4	+		16	45	39	90
L	*B. improvisus*						1	381
	B. eburneus							
	B. sp.				1	+	30	406
S	*B. improvisus*				18	175	8	
	B. eburneus							Lost
	B. sp.	7	1		1,201	179	+	

DEVELOPMENT OF COMMUNITIES

The following descriptions of the development of fouling communities are based on data collected from January to December.

At Station A the initial colonisers were algae *(Ulvaceae)* followed by amphipods and *Tanaidacea.* Barnacles and serpulids occurred on the six month plates. After nine months exposure, red algae replaced green algae and settlement of bryozoans and bivalves also occurred. At the end of the year the fouling community was dominated by a mixture of algae, barnacles, *Crassostrea, Ficopomatus* and amphipods.

At Station B the pattern of the development of the community was similar to that

L E 3

LES DURING 1978 (No/dm^2)

					3	MONTHS			6 M		9 M	12 M
A	S	O	N	D	J-M	A-J	J-S	O-D	J-J	J-D	J-S	J-D
8	+	2				5	17	12	7	14	24	34
							1	+		9	4	7
1		1	1			+		2	+			9
8	+	2			+	3	22	66	19	9	38	15
							2			11	20	18
		+	+		+			16				
	1	3					12	2		13	17	114
6	1	+	+		+			11		9		63
	+		+			+	1		+	1	5	1
+							2			2	1	3
	+	+										
50	18	25	4		44	285	175	61	985	22	86	91
6							18			45	1	38
11		29	17		21	50		60	297			27
271	64	37	12			131	748	26	84	469	189	119
							7			26		
352	26	28	224			25		110	57			32
28		81			9	459	107	44	290	439	112	
+										22		Lost
24		107	3		6	57		1	26			

described for Station A, but *Crassostrea* and barnacles were much more important on the twelve month panels.

At Station C, during the first 3-4 months, only a slime of microalgae was present on the panels. After six months green algae were recorded and then, after nine months barnacles *(B. improvisus)*, amphipods and serpulids. These organisms were also present on the 12 months panel, although *B. improvisus* was largely dominant.

At Station D, algae represented the initial settlers on the 1 and 3 month plates; after 6 months, bryozoans *(Ctenostomata)*, hydroids, *Ficopomatus* and barnacles were dominant. Three months later (9 months) the following

TAB

SETTLEMENT OF "FICOPOMA

						I MONTH	
	J	F	M	A	M	J	J
A							6
B						+	892
C							
D				25	667	38	883
A						+	14
B							
C						8	14
D					196	833	1,167
H					1	17	8
L							96
S						1,100	Lost

TAB

SETTLEMENT OF MOLLUS

							I MONTH	
		J	F	M	A	M	J	J
A	*M. galloprovincialis*							
	C. gigas							
B	*M. galloprovincialis*							
	C. gigas							
C	*M. galloprovincialis*							
	C. gigas							
D	*M. galloprovincialis*							
	C. gigas							
H	*M. galloprovincialis*							
	C. gigas							6
L	*M. galloprovincialis*							
	C. gigas							
S	*M. galloprovincialis*							Lost
	C. gigas							

LE 4

TUS ENIGMATICUS" (No/dm²)

						3 MONTHS			6 M		9 M	12 M
A	*S*	*O*	*N*	*D*	*J-M*	*A-J*	*J-S*	*O-D*	*J-J*	*J-D*	*J-S*	*J-D*
		1977										
		+					142	+	+	533	3	83
2		52	1				21	3		200	1	5
296	375	125	58			506	1,783	125	29	333	30	504
		1978										
45	236	74					196	307	3	217	70	417
			+				5	12	+	16	52	55
47	42	16						1		1	1	1
525	635	139				20	833	108	8	858	625	721
47	71	76	4			12	55	48	13	125	151	46
136	111	20	32				354	408		142	201	92
679	1,492	792				47	17	400	33	367	1,050	Lost

LE 5

CS DURING 1978 (No/dm²)

						3 MONTHS			6 M		9 M	12 M
A	*S*	*O*	*N*	*D*	*J-M*	*A-J*	*J-S*	*O-D*	*J-J*	*J-D*	*J-S*	*J-D*
1	4											
							+			2	1	4
16	53						2			2	4	9
								1				
									+		+	+
122	171	53	1				14	52		34	64	21
								1				
	+						1	2		4		1
						3			7	3	12	
+	+										+	Lost

organisms were added: *Conopeum seurati*, amphipods, *Sphaeroma hoockeri*, *Neanthes succinea* and *Rhodophyta*. On 12 month panels the dominant community was represented by serpulids, barnacles, *Rhodophyta* and bryozoans.

At Station H barnacles were dominant on 1 month to 12 month panels. Other organisms (hydroids, polychaetes, molluscs, amphipods) only became important after 9 months exposure. On 12 month panels the dominant organisms were: barnacles, serpulids, molluscs with hydroids, amphipods and bryozoans.

At Station L, amphipods and algae were present on the plates after only 3 months. After 6 months, barnacles began to be the dominant organisms on the panels while after 9 months these were accompanied by serpulids, amphipods and bryozoans. After 12 months barnacles, *Ficopomatus*, amphipods and *Crassostrea* were dominant.

At Station S, amphipods and barnacles were the first settlers; on 3 month plates algae were also present. On the 6 month panels barnacles, serpulids, amphipods and molluscs were dominant and increased in importance during the 9 and 12 month immersion periods.

AMOUNT OF FOULING

The amount of fouling on the panels was estimated as wet weight; it was not possible to separate the sediment/debris on the panels which was especially important at Station C.

All values measured during 1978 are recorded in Figure 4.

The heaviest wet weights were observed during the summer and the lightest wet weights observed during the winter when sometimes no settlement occurred.

The maximum wet weights recorded were: 40.8 g/dm^2 for one month panels, 185.5 g/dm^2 for 3 month panels, 370.5 g/dm^2 for 6 month planels but only 160.0 g/dm^2 after 12 months exposure, due to the detachment of part (mainly serpulids) of the community.

CONCLUSIONS

Among the macrobenthic animals recorded in the lagoon «Sacca del Canarin» (approximately thirty species) it is likely that *F. enigmaticus*, *B. improvisus*, *B. eburneus*, *C. gigas*, *C. seurati* and *B. gracilis* will be the main fouling species in the conduits of an electric power station presently under construction.

During the second year a larger number of hydroid and amphipod species were observed.

If some changes in the northern part of the lagoon decrease the influence of inflowing freshwater, the resulting increased salinity of the water will allow the additional settlement of *M. galloprovincialis* and this species will also foul the conduits.

The fouling of this lagoon is quite different from that described in the lagoon of Venice (RELINI *et al.*, 1972; BARBARO and FRANCESCON, 1976) and in the harbours of the North Adriatic sea (IGIC, 1969; SPECCHI *et al.*, 1976) probably because the lagoon is strongly influenced by the flow of freshwater from the river Po.

Settlement of marine organisms was generally heaviest during the summer and very light in the winter. Fouling was also observed to be much more abundant in the second year of investigation. The heaviest settlement, in terms of number of individuals and wet weight, occurred at stations more strongly influenced by incoming sea water and was lightest at the stations more strongly influenced by freshwater coming from the river Po. At some stations fouling was closely correlated with the flow rate of the Po river; an increase in the flow rate resulted in a decrease in the settlement of organisms.

SUMMARY

The macrobenthos settling on asbestos panels and various other hard substrata in the lagoon «Sacca del Canarin» (Po river delta, Italy) was investigated over two years between January 1977 and December 1978. The aim of the investigation was to determine which fouling organisms were likely to be present in the conduits of a power station to be built near the lagoon and to evaluate possible changes in the benthic communities living in this brackish environment as a result of its operation.

The lagoon is very shallow (less than 1.5 m) and influenced by both sea water and fresh water (from the river Po) entering at various

sites. The salinity of the lagoon varies considerably but is generally low and sometimes in the northern part does not exceed 1-5 $^0/_{00}$; temperature and nutrient levels can also vary considerably.

The panels were immersed for 1, 3, 6, 9 and 12 monthly intervals at four stations; during the second year three additional stations were investigated. Samples were also regularly collected in each season from natural substrata at twelve stations distributed around the borders of the lagoon. The macrobenthic species recorded on the panels were identical to those collected on the natural hard substrata. Approximately thirty species of animals were identified, half of these in quite large quantities. The main algae present were species of the genera *Enteromorpha, Ulva, Cladophora, Polysiphonia* and *Ectocarpus.*

The main fouling organisms recorded in order of importance were: *Ficopomatus (= Mercierewa) enigmatius* (Fauvel), *Balanus improvisus* Darwin, *Balanus eburneus* Gould, *Crassostrea gigas* (Thunberg), *Echinogammarus* sp., *Leptocheirus pilosus* Zaddach, *Conopeum seurati* (Canu) and *Bowerbankia gracilis* (Leidy).

Settlement of marine organisms was generally heaviest during the summer and very poor in the winter. Fouling was also observed to be much more abundant in the second year of investigation. The heaviest settlement, in terms of number of individuals and wet weight, occurred at stations more strongly influenced by incoming sea water and was lightest at the stations more strongly influenced by freshwater coming from the river Po. At some stations fouling was closely correlated with the flow rate of the Po river; an increase in the flow rate resulted in a decrease in the settlement of organisms.

The maximum wet weights recorded were: 40.8 g/dm² for monthly panels, 18.5 g/dm² for 3 monthly panels, 370.5 g/dm² for 6 monthly panels but only 160.0 g/dm² after 12 months exposure, due to the detachment of part (mainly serpulids) of the community.

RESUME

On a étudié pendant deux années, du Janvier 1977 au Décembre 1978, le macrobenthos installé sur des plaques expérimentales et sur de nombreux autres substrats durs dans la lagune saumâtre «Sacca del Canarin» (delta du Pô, Italie). Les buts de la recherche étaient deux: découvrir les organismes capables de coloniser les conduites de réfroidissement d'une centrale thermo-électrique en construction près de la lagune; évaluer les possibles altérations des communités benthiques lagunaires en conséquence du fonctionnement de la centrale.

La lagune est très peu profonde (moins de 1,5 m); les eaux de la mer et du fleuve Pô y pénètrent par plusieurs points. La salinité de la lagune est très variable, mais généralement elle est faible et parfois dans la partie septentrionale elle n'atteint que 1-5 $^0/_{00}$; même la temperature et la teneur en nutrients sont très variables. Les plaques furent immergées durante 1, 3, 6, 9 et 12 mois en quatre stations; pendant la deuxième année on a aiouté trois autres stations. On a efectué même des prélevements saisonniers sur substrat dur naturel en douze stations le long des bords de la lagune.

Sur les plaques on a récolté les mêmes espèces macrobenthiques qui étaient présentes sur les substrats naturels. On a identifié environ trente espèces animales, dont la moitié comprenait un grand nombre d'individus. Parmi les algues il y avait des espèces de *Enteromorpha,* d'*Ulva,* de *Cladophora,* de *Polysiphonia* et de *Ectocarpus.*

Les organismes les plus abondants dans la salissure étaient, dans l'ordre: *Ficopomatus (= Mercierella) enigmaticus* (Fauvel), *Balanus improvisus* Darwin, *Balanus eburneus* Gould, *Crassostrea gigas* (Thunberg), *Echigommarrus* sp., *Leptocheirus pilosus* Zaddach, *Conopeum seurati* (Canu) et *Bowerbankia gracilis* (Leidy).

La salissure a été plus riche pendant la deuxième année; en général elle était plus abondante en été et très faible en hiver.

Dans les stations soumises à l'influence de la mer soit le nombre des individus soit le poids humide étaient maximaux; au contraire, la salissure était très pauvre près des embouchures du fleuve Pô. Dans quelques stations, la salissure biologique était en correlation stricte avec le régime hydrique du fleuve Pô: un plus grand apport fluvial provoque une installation réduite des organismes.

Les poids humides maximaux observés sur les plaques ont été: 40,8 g/dm² après un mois, 185,5 g/dm² après 3 mois, 370,5 g/dm² après 6 mois, mais seulement 160,0 g/dm² après 12 mois, à cause du détachement d'une partie (surtout les amas de serpuliens) de la salissure.

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LARVAS MEROPLANCTONICAS EN AGUAS DE PUERTOS ITALIANOS

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Italia

El plancton de aguas portuarias resulta caracterizado, especialmente en algunos momentos estacionales, por la presencia elevada de larvas de organismos bentónicos que llegan a ser parte importante del plancton mismo.

Algunos aspectos de esta componente fueron analizados en un trabajo anterior sobre las larvas de cirrípedos (PICONE y ZUNINI SERTORIO, 1976). En la presente nota se examinan por grupos, sin descender al detalle de las especies, las larvas de briozoos, poliquetos, cirrípedos, moluscos, equinodermos y ascidiados, basándose en los datos obtenidos en trabajos sobre zooplancton llevados a cabo en aguas de algunos puertos de la costa de Liguria y de Toscana (Italia). Observaciones mensuales se realizaron, a lo largo de un ciclo anual, en el puerto de Génova (DELLA CROCE *et al.*, 1973) y en la ensenada de La Spezia (GALLO, 1978; FABIANO *et al.*, 1980), y en tres momentos estacionales diferentes, de distintos años, en ocho puertos a lo largo de la costa

TABLA 1

DENSIDADES DE LARVAS POR METRO CUBICO: VALORES MAXIMOS, MINIMOS Y MEDIOS ANUALES

	PUERTO DE GENOVA (CINCO ESTACIONES)				RADA DE LA SPEZIA (TRES ESTACIONES)			
	Máx.	*Mín.*	*Media*	*%*	*Máx.*	*Mín.*	*Media*	*%*
Poliquetos	2.437	133	1.120	7,2	1.193	148	454	4,9
Cirrípedos	2.750	30	820	5,3	971	63	375	4,1
Lamelibranquios.	497	17	157	1,0	908	42	268	2,9
Ascidiados	668	0	116	0,7	10	0	2	<0,1
Briozoos	280	0	35	0,2	53	0	10	0,1
Gasterópodos ...	83	0	23	0,1	10	0	2	<0,1
Equinodermos ...	49	0	8	<0,1	0	0	0	0

Los porcentajes se refieren a los valores medios sobre los totales de zooplancton.

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de Liguria y de Toscana (Picone *et al.*, 1978; Basso *et al.*, 1980; Cevasco *et al.*, 1980) (figura 1). En el presente trabajo sólo se utilizan los datos obtenidos de muestras cuantitativas tomadas con botella (10,5 litros) a distintas profundidades, filtradas a través de red con mallas de 92 micras.

OBSERVACIONES ANUALES

Las larvas de animales bentónicos aquí consideradas representan en el puerto de Génova, en promedio anual, el 14,7 % del zooplancton y varían, en el curso del año, del 5,7 % en agosto al 48,8 % en diciembre; en La Spezia representan el 12,1 % y varían del 7,5 % en agosto al 20,2 % en febrero. El tanto por ciento del número de larvas sobre el total de zooplancton es mínimo en verano (8 % en ambos lugares) y máximo en otoño (28 y 17 %, respectivamente, en Génova y en La Spezia).

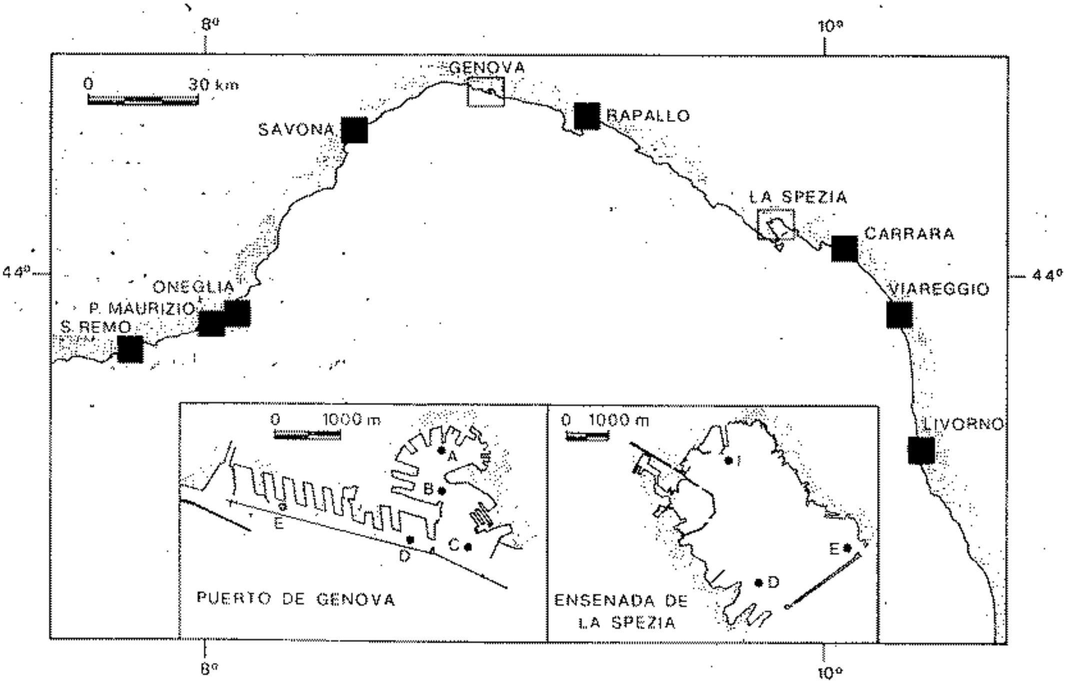

Fig. 1.—Ubicación de los puertos estudiados.

En las aguas de las dos localidades, las larvas más numerosas son las de poliquetos, de cirrípedos y de lamelibranquios; las de ascidiados y de briozoos caracterizan cuantitativamente sólo el puerto de Génova. Las larvas de equinodermos han resultado muy escasas en Génova y no se han hallado en La Spezia (tabla 1).

La presencia de larvas a lo largo de todo el año se caracteriza por densidades mayores en primavera, decrecientes en verano y bajas en las demás estaciones. Sin embargo, se observa un apreciable aumento de las densidades en otoño en La Spezia y a principios de invierno en Génova. En las aguas de esta última localidad, las concentraciones observadas en el curso del año oscilan entre 0,5 y 4,9 × $10^3/m^3$ y en promedio anual; la cantidad de larvas es aproximadamente doble de la hallada en la ensenada de La Spezia, donde las concentraciones varían de 0,4 a 2,8 × $10^3/m^3$ (fig. 2, 1).

En las zonas internas de ambas localidades, las concentraciones promedias anuales por metro cúbico alcanzan valores dos-tres veces más altos que en las zonas próximas al mar libre, según queda reflejado en el cuadro siguiente (la posición de las estaciones está señalada en la figura 1):

Localidad	*Estación*	*Larvas/m*^{3}
Puerto de Génova	A	2.850
	B	2.950
	C	1.439
	D	1.347
	E	2.797
Rada de La Spezia	I	1.890
	E	847
	D	592

Estas mayores densidades, que se verifican tan sólo en algunos momentos del año, son causadas, sobre todo, por las larvas de poliquetos (fig. 2, 2) y de cirrípedos (fig. 3); solamente en La Spezia, pero en medida mucho menor, en ellas participan también las larvas de lamelibranquios.

En promedio anual, la densidad de larvas de poliquetos es, respectivamente en Génova y en La Spezia, 2,4 y 2,8 veces mayor en las zonas más internas; la de cirrípedos, 1,8 y 4,8 veces *. Sin embargo, en algunas muestras mensuales estos valores llegan a ser aún mayores de 10.

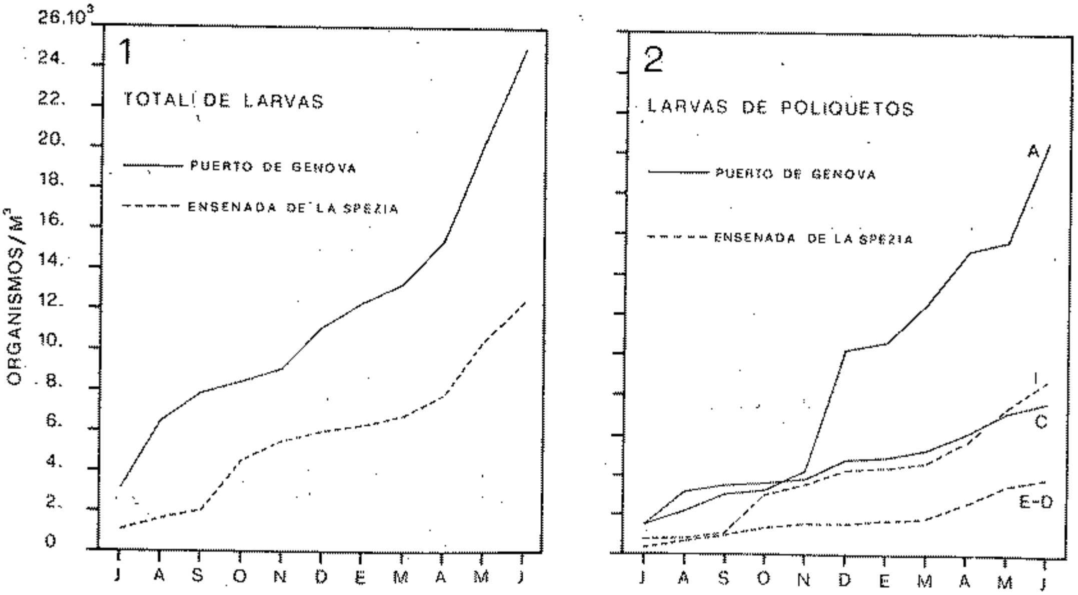

FIG. 2.—Curvas acumulativas de las densidades de larvas/m^3 (se omite el mes de febrero, faltando los datos del puerto de Génova). 1. Puerto de Génova y ensenada de La Spezia. 2. Comparación entre zonas internas y zonas próximas al mar libre. Génova, estación interna (A), antepuerto (C); La Spezia, estación interna (I), promedio de los valores entre las dos estaciones próximas a las bocanas (E-D).

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* Las comparaciones utilizan: en Génova, los datos de las estaciones más interna y del antepuerto; en La Spezia, los de la estación interna, y del promedio de los valores, de las estaciones próximas a dos bocanas (fig. 1).

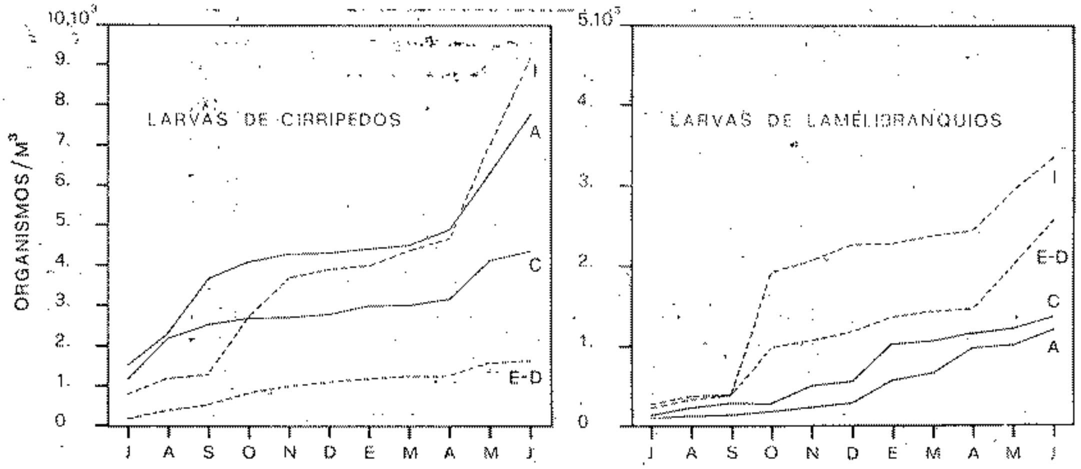

FIG. 3.—Curvas acumulativas de densidades de larvas/m³. Las curvas se refieren a las mismas estaciones indicadas en la figura 2.

Las observaciones estacionales llevadas a cabo en aguas de los puertos de Livorno, Viareggio y Savona confirman estos hechos: también allí las larvas de poliquetos, de cirrípedos y de lamelibranquios pueden alcanzar, en las zonas más internas, densidades varias veces mayores que en las zonas próximas a las aguas libres.[*].

Otra es la situación que se encuentra al observar los demás grupos de larvas. En Génova, las larvas de lamelibranquios, ascidiados y gasterópodos alcanzan concentraciones promedias anuales poco diferentes en las distintas zonas portuarias, hallándose sólo los *Cyphonautes* en mayores cantidades en el antepuerto. En las aguas de La Spezia, la cantidad de esos grupos de larvas, con la excepción de las de lamelibranquios, es tan escasa que no da posibilidad a comentarios.

La «facies» de las larvas meroplanctónicas (figura 4), en promedio anual, difiere, sobre todo, por la mayor participación de las larvas de lamelibranquios en La Spezia[**] y de las de ascidiados y briozoos en Génova. El *trend* que se observa en los dos lugares a lo largo del año pone de manifiesto diferencias que se hacen más notables en otoño e invierno, cuando en Génova se observa una fuerte preponderancia de larvas de poliquetos y en La Spezia la casi totalidad de la población larval está formada por las de poliquetos, de cirrípedos y de lamelibranquios, que se encuentran presentes en cantidades similares.

OBSERVACIONES ESTACIONALES

En los otros ocho puertos, el porcentaje de las larvas sobre el total del zooplancton oscila del 3 al 46 % en todas las muestras tomadas en los tres diferentes momentos estacionales. El examen de los datos, además de poner de manifiesto tan grande variabilidad en la participación del componente larval, indica que éste alcanza hasta el 26 % en otoño (Livorno), el 46 % en primavera (Oneglia) y el 43 % en verano (Viareggio).

El promedio del número de larvas/m³ de los tres momentos estacionales resulta ser:

Viareggio	3,4 × 10³
Savona	3,4
Oneglia	2,5
Livorno	2,1
Porto Maurizio	1,7 × 10³
San Remo	1,4
Carrara	1,1
Rapallo	0,7

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[*] En estos puertos, como en el de Génova y en la ensenada de La Spezia, se ubicó más de una estación.

[**] Existen parques mejilloneros en la ensenada.

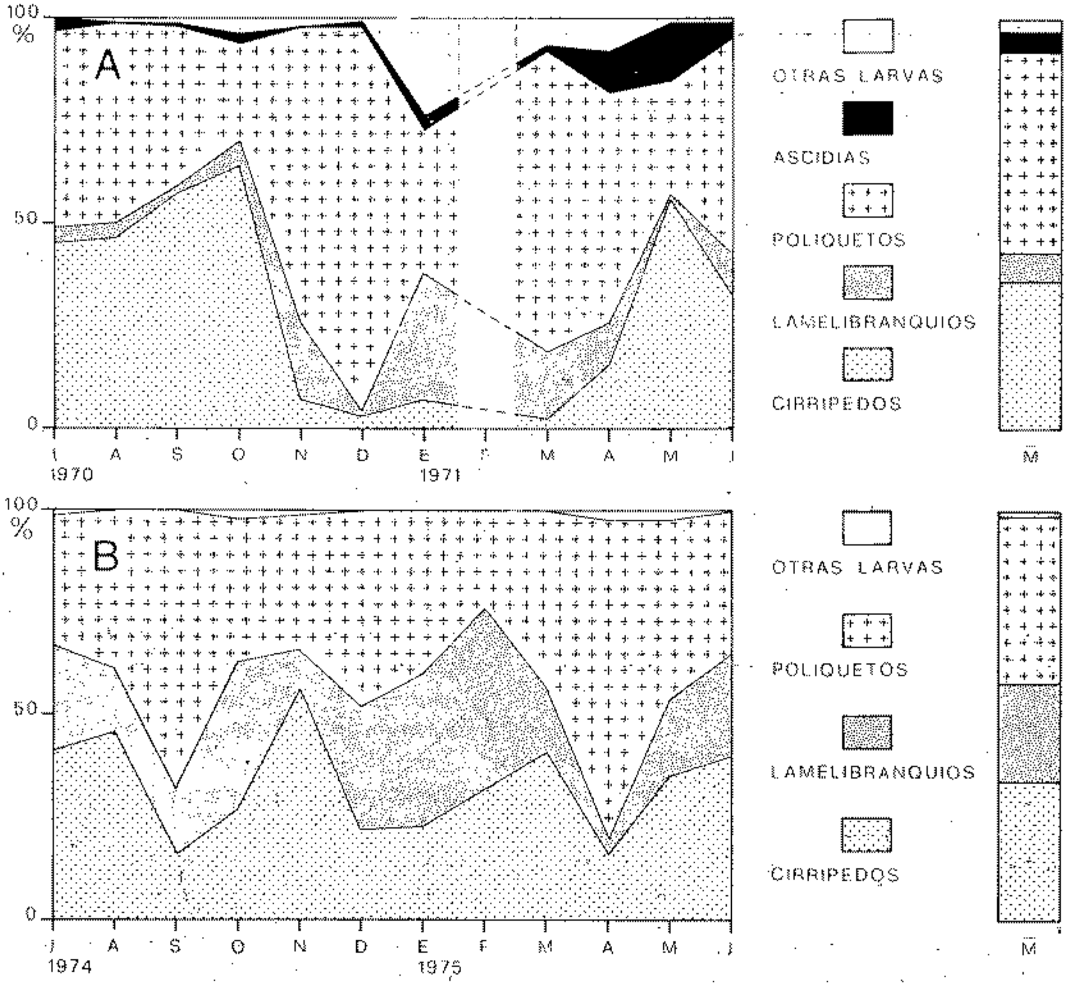

FIG. 4.—Composición mensual y composición promedia anual (M) de la población larval meroplanctónica: A. Puerto de Génova. B. Ensenada de La Spezia.

En cada uno de los puertos, las larvas pueden contarse por millares/m³ en el momento estival y por centenares en el otoñal; están presentes otra vez por millares en el momento primaveral, excepto en los puertos de San Remo y Rapallo (0,7 y 0,5 × 10³).

En verano, las fuertes densidades de larvas observadas en los puertos de Savona, Viareggio y Livorno (de 3,2 a 7,7 × 10³/m³) se deben principalmente a las larvas de poliquetos y de cirrípedos. En los puertos de San Remo, Oneglia, Rapallo y Carrara (con densidades de larvas entre 1,1 y 2,6 × 10³/m³) son las de lamelibranquios y gasterópodos las que dominan, siendo las de poliquetos y cirrípedos presentes en cantidades reducidas.

En otoño y primavera, las larvas de poliquetos constituyen elemento preponderante en la gran mayoría de los puertos y casi siempre están acompañadas por larvas de lamelibranquios. Hay que señalar, además, que las larvas de cirrípedos disminuyen y a veces no aparecen en las muestras de otoño y que las de briozoos se encuentran con más abundancia en el momento primaveral. Las larvas de equinodermos siempre han resultado numéricamente insignificantes (tabla 2).

CONCLUSIONES

En las aguas de los puertos que han sido objeto de esta nota, las larvas meroplanctónicas examinadas alcanzan en primavera, en su conjunto, las máximas densidades por metro cúbico.

Las larvas de poliquetos, de cirrípedos y de lamelibranquios resultan ser las más importantes cuantitativamente. Ellas alcanzan las mayores concentraciones en las zonas internas y más protegidas de los puertos, llegando, como máximo, las de poliquetos a $6{,}2 \times 10^3/m^3$ (Génova, diciembre); las de cirrípedos, a $9{,}0 \times 10^3/m^3$ (Viareggio, julio), y las de lamelibranquios, a $1{,}8 \times 10^3/m^3$ (Livorno, julio). Las larvas de poliquetos y de lamelibranquios siempre se encuentran presentes en el plancton

TABLA 2

DENSIDAD DE LARVAS/m³ EN MUESTRAS ESTACIONALES TOMADAS EN VERANO (V), OTOÑO (O) Y PRIMAVERA (P)

	Estación	*San Remo*	*Porto Maurizio*	*Oneglia*	*Savona*	*Rapallo*	*Carrara*	*Viareggio*	*Livorno*
Poliquetos	V	190	807	190	1.720	332	190	1.852	1.305
	O	522	380	332	897	190	47	380	424
	P	332	1.757	3.562	3.420	0	1.092	1.710	1.510
Cirrípedos	V	0	142	237	1.008	47	47	5.367	722
	O	0	285	0	164	95	0	47	57
	P	47	142	47	242	237	570	285	541
Lamelibranquios	V	950	712	1.235	818	950	332	396	918
	O	142	190	237	74	47	190	0	66
	P	237	95	475	1.092	190	190	127	367
Gasterópodos	V	1.425	237	902	84	0	522	0	212
	O	0	0	0	0	0	0	0	0
	P	0	95	0	37	0	0	0	19
Briozoos	V	0	0	0	0	47	0	0	0
	O	47	47	0	0	0	0	0	0
	P	95	95	190	691	0	47	16	60
Ascidiados	V	47	0	0	74	47	0	127	38
	O	47	0	0	10	0	0	0	0
	P	0	0	0	0	0	0	31	0

de los puertos, pudiendo las de cirrípedos desaparecer en otoño e invierno.

Los grupos de larvas encontrados con menor frecuencia y abundancia son los de gasterópodos, briozoos y ascidiados. Por lo que hace referencia a los gasterópodos, la máxima cantidad de larvas se halla en verano, con concentraciones a veces elevadas (San Remo, $1{,}4 \times 10^3/m^3$). Las larvas de briozoos aparecen en cantidades más abundantes en invierno ($0{,}7 \times 10^3/m^3$, Génova) y en primavera ($0{,}7 \times \times 10^3/m^3$, Savona); las de ascidiados, en primavera ($0{,}7 \times 10^3/m^3$, Génova).

En el puerto de Génova, la densidad de larvas, en media anual, resulta más alta que en la ensenada de La Spezia (respectivamente, $2{,}3 \times 10^3$ y $1{,}1 \times 10^3/m^3$). Este hecho hace pensar que en la primera localidad se llegue a una alta colonización de bentos, incluyendo al *fouling*. Cabe señalar que también la población de copépodos, en promedio anual, resulta ser más del 50 % mayor en Génova que en La Spezia ($10{,}7 \times 10^3$ y $4{,}6 \times 10^3/m^3$), lo que pondría de manifiesto que las aguas de la ensenada sólo logran sustentar una carga biológica menor.

El tanto por ciento de larvas meroplanctónicas sobre el total del zooplancton resulta muy variable, no ofreciendo posibilidad de esquematización. Su participación al plancton parece más bien ligada a ciclos reproductivos.

Por lo general, las larvas de poliquetos y a veces las de cirrípedos predominan entre las larvas meroplanctónicas; sólo en algunos puertos, en verano, se observa una preponderancia de larvas de moluscos.

Nuestros anteriores estudios sobre el plancton de aguas portuarias han puesto de manifiesto las dificultades de correlación entre los parámetros ecológicos examinados y los aspectos estructurales y cuantitativos de las poblaciones de copépodos. Nuevamente se nos presenta este problema en lo que hace referencia la componente larval meroplanctónica, más estrictamente ligada, por su naturaleza, a específicas exigencias ambientales. Hasta ahora no se han evaluado con suficiente exactitud factores tales como la tasa de renovación de las aguas, la morfología de los puertos y el efecto de la inmisión de aguas de origen urbano e industrial, factores todos que pueden tener una importancia mayor en influenciar la facies del plancton portuario.

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BIOFOULING IN A NORTH-CENTRAL CHILEAN COASTAL BAY

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SUMMARY

Herradura Bay is a small semi-enclosed coastal water body which, due to its protected shore, enriched water, and unknown factors supports unusually intense biofouling. Preliminary information demonstrates high species diversity in the fouling community, and its rapid rate of accumulation. Fouling of lines, netting and seawater piping used in experimental mariculture has resulted in serious impairment of mariculture development.

INTRODUCTION

Herradura Bay is a small, semi-enclosed bay on the central Chilean coast, adjacent to the city of Coquimbo at 29° 59' S and 71° 22' W. The bay is almost symmetrically horseshoe shaped (hence the name), with steep rocky shoreline on both sides, and has a total surface area of 3.3 km². The bay mouth is about 0.7 km wide, opening to a maximum inside width of 1.8 km. Median depth of the bay is 19 m with a uniform benthic slope shoreward to sandy beaches on its S-SE margin. The slope seaward leads to a maximum depth of 60 m at the bay mouth. The bay bottom consists of varying grades of sandy sediments containing a significant calcareous fraction.

Little fresh water flows into the bay, and its water conditions are dominated by oceanic water masses. Circulation patterns in the bay are relatively weak, apparently dominated by tidal flushing. In a year-long survey in 1976-77 (Alfsen, 1979) found surface maximum temperatures to fluctuate between 21.08° C (January) and 13.29° C (September), and bottom temperature extremes from 15.8° C (March) to 11.46° C (October). Marked temperature stratification was evident with summer warming of inner bay surface waters. Oxygen values were rarely below 100 % saturation. Salinity averaged 34.462 ‰, showing only minor variation with depth and season.

Approximately three quarters of the bay shore is given to recreational usage, residential area, or remains undeveloped. The N-NE quadrant of the bay is developed, including a major fishery, a small power plant, and a bulk iron ore loading facility. It also is the site of a primary sewage outfall serving 15,000 inhabitants. These and the relatively minor shipping associated with them are contributors of contaminants to the otherwise pristine oceanic waters.

The Centro de Investigaciones Submarinas of the Universidad del Norte is also located in the N-NE quadrant of the bay shore. This developing marine research station has concerned itself with studies on the culture of local and exotic mollusc species of potential commercial importance to Chile. The bay waters have proved to be highly amenable to the culture of filter feeding molluscs from egg to adult due to the rich plankton fauna in the ambient water, apparent absence of toxic substances in the water, and high overall water quality for the artificial culture of microalgal feeds.

TABLE I

MAIN SEDENTARY OR ENCRUSTING FOULING ORGANISMS IN HERRADURA BAY, CHILE

Grouping	*Species or characteristics*
Bacterial films	Abundant, unidentified.
Algae	Diatoms *. *Enteromorpha sp., Ectocarpus sp., Lithothamnium sp., Heterosiphonia sp.,* Ralfsiaceae.
Sponges	*Leucosolenia variabilis.*
Hydroids	*Tubularia sp., Obelia sp., Campanularia sp.*
Bryozoans	*Bugula neritina, B. flabellata, B. californica, Umbonula alvareziana.*
Arthropods	*Megabalanus psittacus, Balanus laevis, Corophium sp.*
Molluscs	*Semimytilus algosus, Hormomya granulata, Crepipatella dilatata, Calyptraea trochiformis.*
Polychaetes	*Romanchella pustulata, Nicholaea chilensis, Halosydna patagonica.*
Hemichordates	*Pyura chilensis, Corella eumyota, Paramolgula chilensis, Asterocarpa cerea.*

* Diverse spp.

In spite of almost ideal conditions for growth and development of molluscan species in mariculture, serious fouling problems have arisen due to the unique conditions for the growth of filter feeding organisms in this bay. Oceanic wind and current conditions in the region cause local nutrient upwelling, which spurs primary production in the bay water. The semiprotected nature of the bay provides an unstressed environment for most Chilean coastal species, and conditions which promote appearance of fugitive species from the Magellanic biogeographical province which begins about 800 km to the south at the Strait of Chacao. Furthermore, a number of cosmopolitan fouling species have arrived, apparently with shipping, and have found favorable niches in the bay.

This report presents some preliminary information on occurrence and effects of biofouling in Herradura Bay.

THE FOULING COMMUNITY

A 13 month study of the fouling community was carried out in 1977-78 using acrylic plates suspended from the iron ore loading pier (DuBois, 1979). A total of 81 species was recorded, of which 51 species were encrusting forms. Test plates placed from 1 to 5 meters depth showed total wet weight fouling accumulations of between 0.01 and 0.06 grams per cm² per month. Peak amounts appeared in summer months at shallower placement depths. Long term accumulation plates showed more rapid rates of fouling accumulation in summer, followed by gradual linear increases during the remainder of the year. Average total wet weight accumulations approached 1.0 g per cm² surface in 12 months. Maximum values obtained in near surface waters reached 3.3 g per cm² in 12 months.

Further studies carried out in front of the CIS laboratory in 1977-78 at 1 m from the surface showed maximum fouling accumulations of 0.06 g per cm² in each of the months of February 1977 and 1978. Table 1 lists the fouling organisms most commonly seen and which were of significant quantitative importance.

Fixation and growth of diatoms and *Ectocarpus sp.* was relatively constant over the year. Hydrozoans showed a marked peak of fixation in February, and second peak in fixation from May to July. *Bugula spp.* became apparent mainly in summer months from December to March with minor recruitment in July and August. *Romanchella pustulata* built calcareous tubes during the winter until the be-

TABLE 2

COMPARATIVE FOULING BIOMASS OCCURRING IN 8 cm DIAMETER LABORATORY SEAWATER INTAKE PIPING PLACED AT 10 m DEPTH IN N-NE HERRADURA BAY IN 1979

8 JUNE - 22 AUGUST		24 AUGUST - 12 NOVEMBER	
Meter *	*Biomass (g/cm)* **	*Meter*	*Biomass (g/cm)*
1	45	1	106
15	7	11	12
31	2	20	4

* Distance from intake.

** Drained wet weight.

FIG. 1.—Juvenile *M. psittacus* fouling plastic mesh of holding cage used in scallop mariculture. Approximately one month after immersion at 2 m, winter 1979.

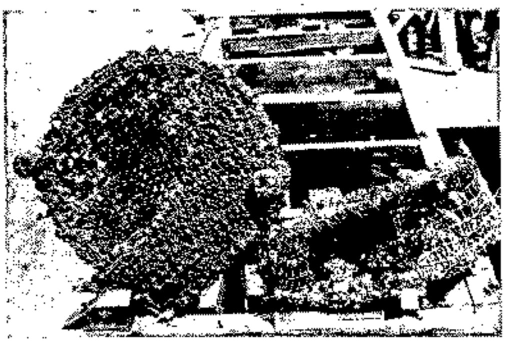

FIG. 2.—Experimental growth cage used in scallop mariculture research, fouled with *M. psittacus* 3 months in fall 1979, depth approx 1 m.

ginning of spring, disappearing from February to May. *Balanus laevis* concentrated during July and December. *Megabalanus psittacus* showed little settlement in February-March 1976, April-May 1977, and February-March 1978.

However, in spring 1979 this species set abundantly, demonstrating irregularity in settlement of this organism. In periods of active setting, *M. psittacus* showed remarkable growth rates. An average of 6 fouling test plates placed in the bay at a level of 1 m in August 1977 acquired an average of 2147 g of biofouling by April 1978 of which approximately 87 % was *M. psittacus*. Average basal diameters of these barnacles was 18.3 mm in 90 days.

The most common fouling succession observed has been fixation of *M. psittacus*, followed by settlement of the tunicate *Pyura chilensis* which successfully competes for substrate with the barnacle, often smothering it. The mussel *Semimytilus algosus* settles and develops well on encrustations of *P. chilensis*.

INTERFERENCE WITH MARICULTURE EXPERIMENTS

Conditions in Herradura Bay which favour growth of commercially valuable species in mariculture, also favour paralyzing development of biofouling on materials used in field test culture systems. For example, fish netting used to contain juvenile bivalves for growout became rapidly fouled with the three *Bugula* species listed in Table 1. These formed dense mats that blocked water exchange through the nets, smothering the organisms in culture. Secondary foulers were colonial tunicates and the hydrozoan *Tubularia sp.*

Plastic screening was primarily fouled by hydrozoans and bryozoans, but was most seriously impaired by development of *M. psittacus* (Figs. 1 and 2). Hemp rope characteristically attracted *Pyura chilensis* and *Semimytilus algosus*. For example, a 1 m length of rope suspended 8 months in the bay developed a mass of *P. chilensis* and *S. algosus* weighing 4.8 kg. Laboratory seawater plumbing, constructed of PVC plastic became rapidly fouled with *Romanchella pustulata* and *M. psittacus*.

BLOCKAGE OF SEAWATER INTAKE

Recruitment of *M. psittacus*, followed by their rapid growth resulted in urgent necessity

FIG. 3.—Plastic (PVC) seawater piping fouled with *M. psittacus, B. laevis,* and tubiculous polychaetes, 75 days in winter 1979 (× 1.25).

to redesign and implement fouling control in the CIS seawater system. Raw seawater was pumped through PVC plastic piping having an internal diameter of 8 cm and length of 220 m. The initial flow rate obtained with a 1 hp pump was 120 l/min. Within 75 days of continuous flow pumping of seawater to the CIS laboratory from June through August 1979 the flow rate had been reduced to 40 l/min. Inspection sampling of the distal 33 m of pipe showed heavy internal fouling by *M. psittacus* and *R. pustulata* which had reduced the intake orifice to 20-25 mm over the first meter of pipe (Fig. 3). When the pipe was replaced in spring, similar conditions rendered the piping unserviceable in 80 days. Table 2 lists quantities of biofouling harvested from cross sections of the intake pipes.

DISCUSSION

To our knowledge, this is the first published listing of main fouling species from a protected bay on the north Chilean coast. In the southern biogeographical region (Magellanic province), beginning near Puerto Montt (42° S) main fouling species which impede mariculture are *Elminius kingii, Cordylophora sp.* and *Conopeum sp.* (Viviani, unpub. data). *Balanus amphitrite* replaces *M. psittacus* in estuarine zones in the south. Neither *E. kingii* nor *B. amphitrite* occurs in Herradura Bay. Various tunicates are of importance in the south of Chile, of which only *Paramolgula chilensis* occurs infrequently in Herradura Bay. *Didemnum spp.* which present problems in southern Chile are scarce in Herradura Bay, occurring either as relicts or as newly introduced species. Encrusting Alcyonarians, important in the south, are absent from Herradura Bay. *Megabalanus psittacus* and *Pyura chilensis* which are so important in Herradura Bay occur and present problems over the majority of the Chilean coastline.

Data on total fouling on experimental plates suggests that the fouling in the bay is probably among the highest rates recorded. Herradura Bay is empirically known as one of the worst areas for fouling on the entire Chilean coast by fishermen and persons responsible for maintenance of fishing fleets. Trawlers from the fishery on Herradura Bay (Coloso Co.) show higher rates of fouling than any other fleet in Chile according to Company representatives. Even using strong organometallic antifouling paints (Hempel Co. #7640) the company has been required to drydock fishing vessels every 8 months for hull cleaning. *M. psittacus* growing on these boats commonly reach 15 cm in height within 8 months. Seawater lines of the Coloso Co. processing plant must be cleaned of fouling every three months.

Methods are now being implemented for the elimination of fouling in CIS laboratory water lines by the use of sand filtration systems at water intakes. Problems associated with mariculture experiments have no simple solution. Use of antifouling compounds in close proximity to cultured organisms is out of the question. Cleaning barnacles from nets and screens is difficult and damaging to the materials. At present, the only feasible solution has been the use of natural strategies for avoiding fouling problems. The most promising mariculture venture at present is the culture in the laboratory of juvenile scallops (*Argopecten purpuratus*), followed by seeding of juveniles into benthic «corrals» where fouling is minimized by the life habits of the scallops. Another solution is the culture of the japanese oyster *Crassostrea gigas,* which has shown potential for growing under silty conditions where fouling is minimal, as well as growing to market size before shell fouling becomes well developed.

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FOULING IN THE SUEZ CANAL

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INTRODUCTION

Since the Cambridge Expedition (Fox, 1926) which lasted only for a few months and investigated benthic communities in the Suez Canal, no similar study has been done. All investigations made so far on this important international waterway have been mainly dealing with its hydrography (Morcos, 1967 and 1973; Morcos and Gerges, 1968 and 1974; Morcos and Messieh, 1973, and Gerges, 1976), and with its plankton populations (MacDonald, 1933; Ghazzawi, 1939, and Dowidar, 1971 and 1976). These investigations have shown that the current regime in the Canal had been northward in the majority of year and for few months, namely from July to October, a reversed current occurs. Damming of the river Nile made this latter current no longer taking place. The salinity is about 39 ‰ in Port Said, about 46 ‰ in the Bitter Lakes and about 42 ‰ in the Suez Gulf. Regarding the phytoplankton large number of species have been recorded but the standing crop decreases from the north to the south. Many species found in the canal are endemic in both Red Sea and Mediterranean and hence the problem of immigration of species from one end to the other is difficult to be explained.

The present review is the first to deal with the year fouling inhabiting the Suez Canal. This waterway can function as a route for the transportation of sessile animals and plants, by being attached to traversing ships, from one end of the world to the other. For instance, the australian immigrant barnacle *Elminius modestus* Darwin, spreading now in the north European waters (Crisp, 1958), its immigration is thought to have been through the Suez Canal. Many of the foulers inhabiting the Canal may thus be imported to it from other parts of the world and during navigation traversing ships will become infected by fouling growths and carry them to seas perhaps have been previously free of it. Consequently, this work becomes necessary when bearing in mind the effect of both the Canal and its fouling on the world navigation.

MATERIALS AND METHODS

Suez Canal, 162 km long, situated between the latitudes 29° 55′ and 31° 16′ and at the longitude 32° 20′, is bordered in the north by Port Said on the Mediterranean Sea, in the south by Suez on the Red Sea and nearly at its middle lies Ismailia on Timsah lake (Figure 1). On the waterway between Port Said and Ismailia six pilotage stations are built by the Canal authorities for guiding the passing ships. These stations are built about 10 km equidistantly separated and are located at Ras El Ish, El Tina, El Cap, El Kantara, El Bellah and El Ferdan. Similarly, five stations are built between Ismailia and Suez. These stations are located at Tossoum, Devresoir, Kebret, Ge-

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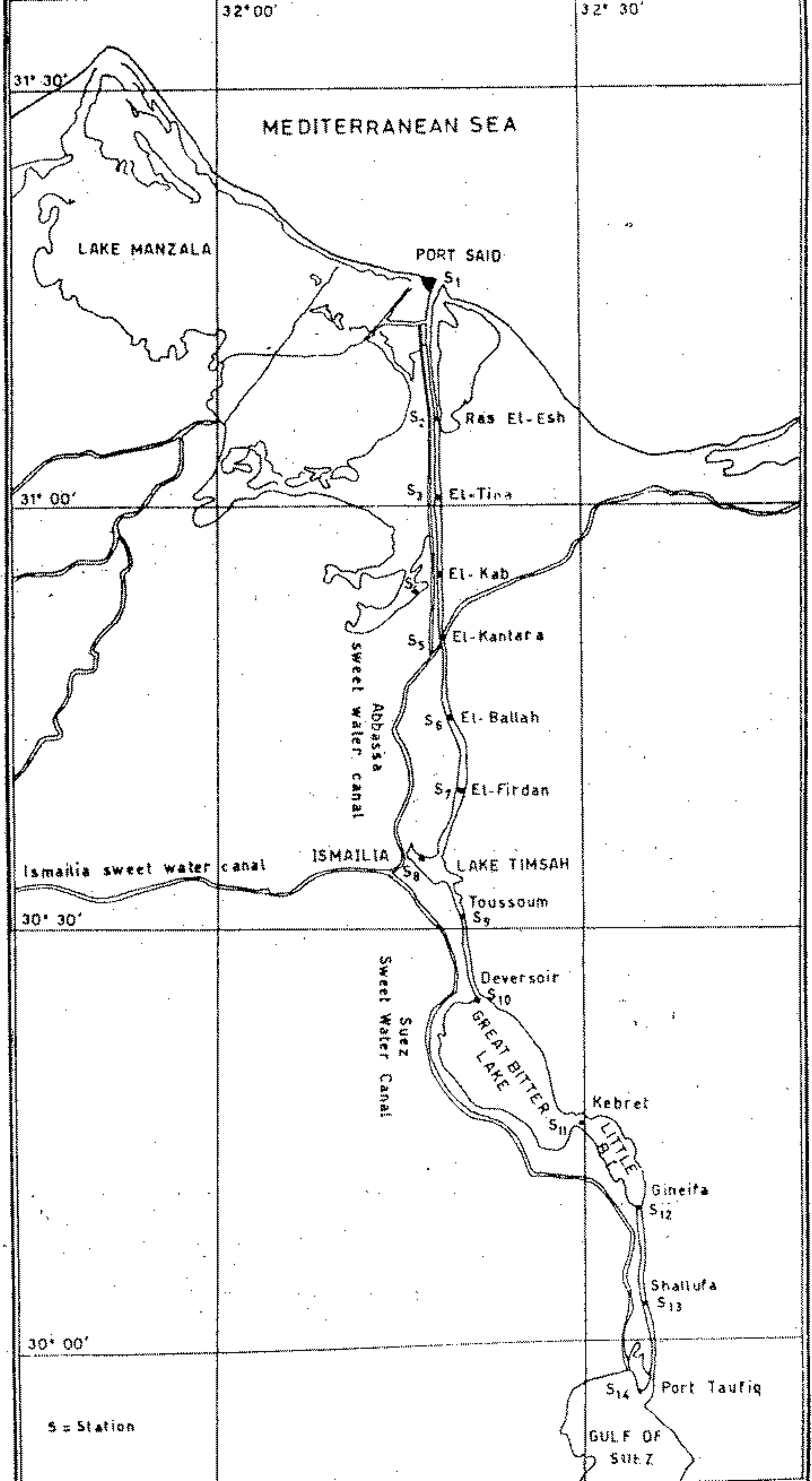
32° 00'
32° 30'
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MEDITERRANEAN SEA
LAKE MANZALA
PORT SAID
S_1
S_2
Ras El-Esh
S_3
El-Tina
31° 00'
El-Kab
S_4
S_5
El-Kantara
Abbassa sweet water canal
S_6
El-Ballah
S_7
El-Firdan
ISMAILIA
Ismailia sweet water canal
S_8
LAKE TIMSAH
Toussoum
S_9
30° 30'
Suez Sweet Water Canal
Deversoir
S_{10}
GREAT BITTER LAKE
Kebret
S_{11}
LITTLE B.L.
Gineifa
S_{12}
Shallufa
S_{13}
30° 00'
S_{14}
Port Taufiq
S = Station
GULF OF SUEZ

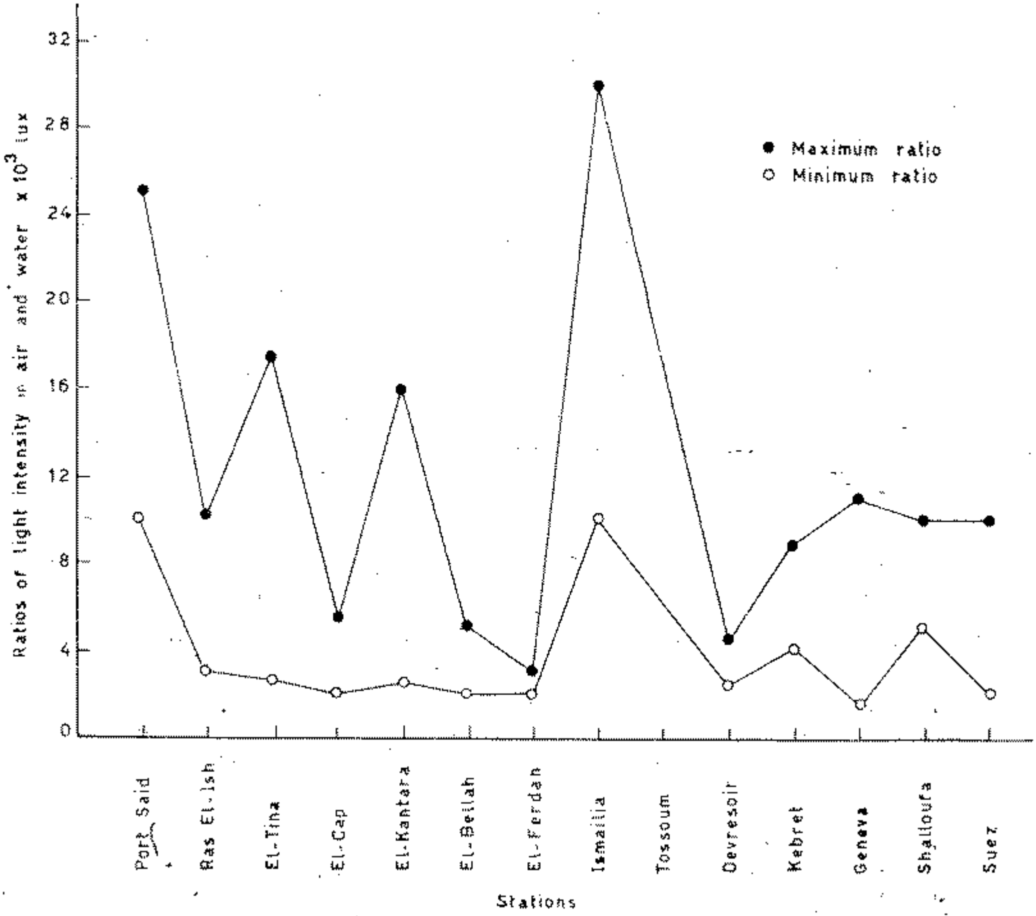

FIG. 2.—The ratios between the values of light intensities in air and in water 5 cm below the surface in 13 stations.

neva and El Shalloufa. From these 11 locations and from the three principal harbours (Port Said, Ismailia and Suez) fouling was periodically qualitatively and quantitatively sampled. A raft 7 m long, 4.5 m wide and 0.8 high (Abdel Malek and Ghanem, 1975) has been moored in each harbour of Port Said, Ismailia (in lake Timsah) and in Suez (near the southern entrance of the Canal). Five exposure panels, 12.5 × 12.5 cm each, made of impact resistant polystyrene were investigated for fouling organisms attached after about a month immersion below the sea surface in each raft. Other test panels were exposed to find out the settlement during 2-12 successive months, at different depths and settlers responses to various environmental variables such as background illuminaton, surface angle and surface contour. The present paper contains only the results representing the settlement rate of the prevailing macrofouling organisms and found on the test panels mounted monthly from January 1977 to July 1978 and all other results will be published elsewhere.

In the intermediate pilotage stations a set of four panels was suspended underneath the

FIG. 1.—A map showing the Suez Canal and the fourteen locations investigated for fouling during this work.

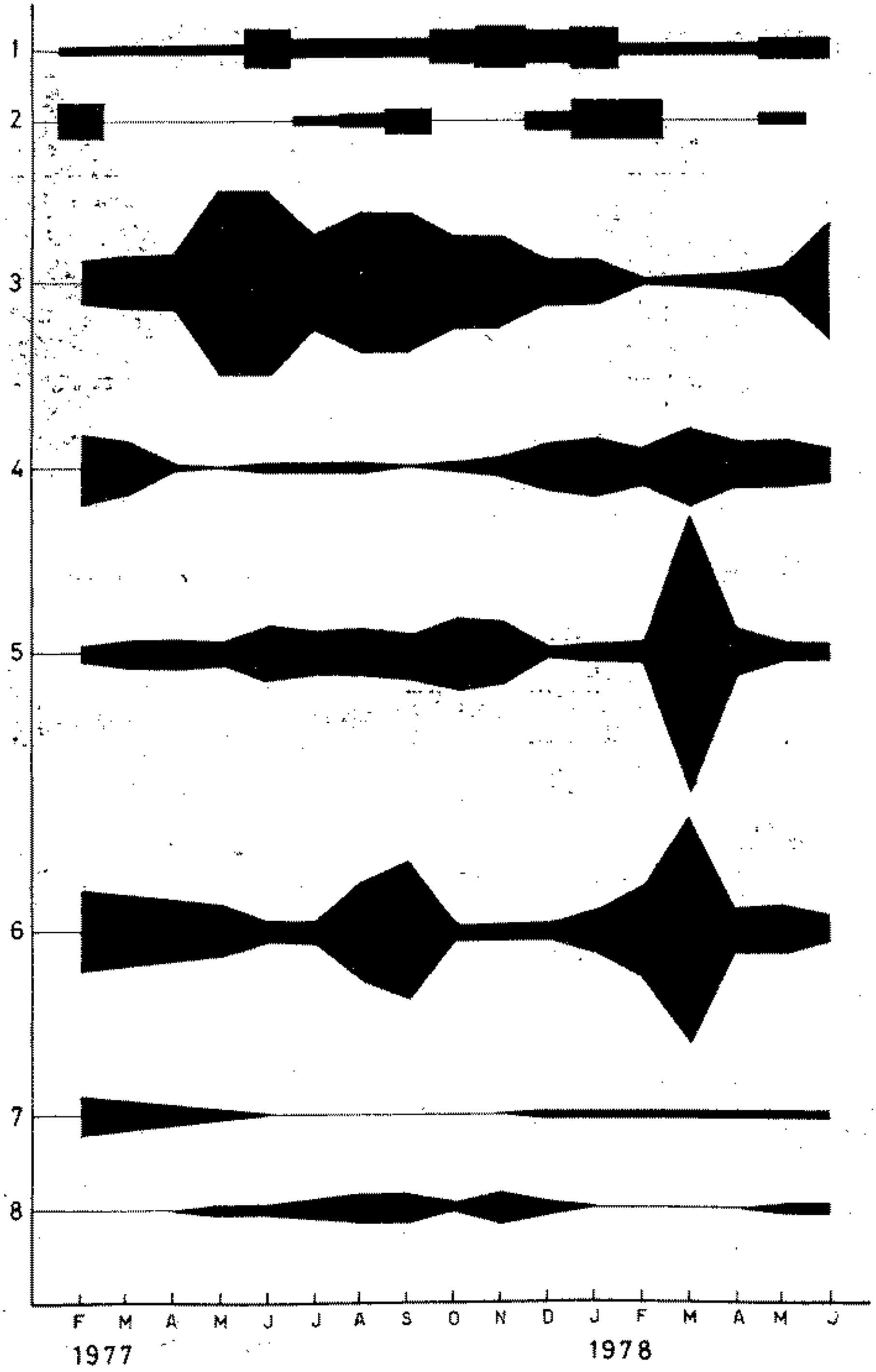

FIG. 3.—Settlement rate of the principal fouling organisms at Port Said Station. Ordinates are proportional to the square roots of the values of the settlement estimated to take place per panel per month: 1) Algae. 2) Hydroids. 3) Serpulids. 4) *Bugula neritina*. 5) Barnacles. 6) Amphipods. 7) *Ciona intestinalis*. 8) Ascidians.

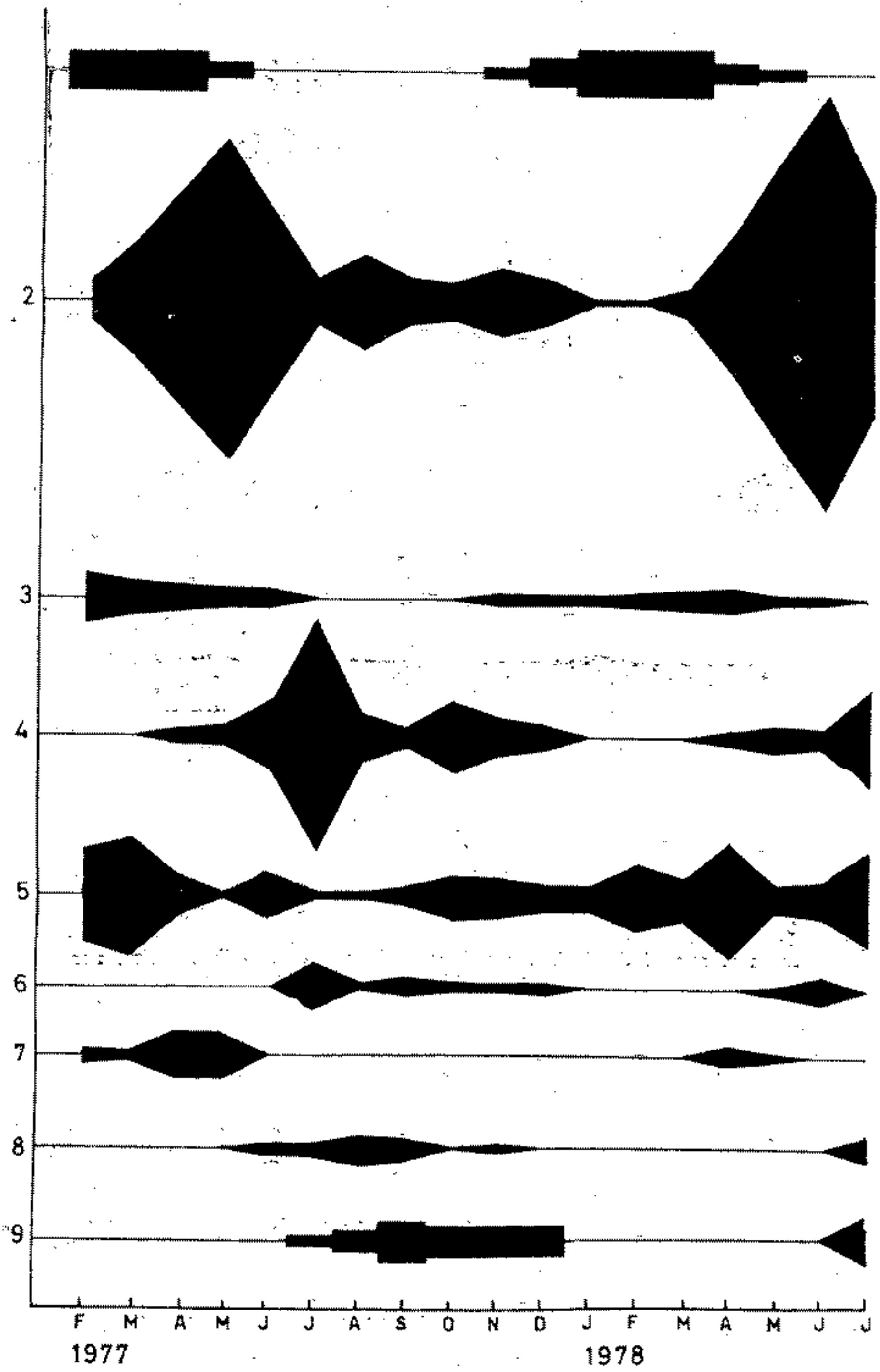

FIG. 4.—Settlement rate of the principal fouling organisms at Ismailia station. Ordinates are proportional to the square roots of the values of the settlement estimated to take place per panel per month: 1) Algae. 2) *Hydroides elegans*. 3) *Bugula*. 4) Barnacles. 5) Amphipods. 6) Bivalves. 7) *Ciona intestinalis*. 8) Solitary ascidians. 9) Colonial ascidians.

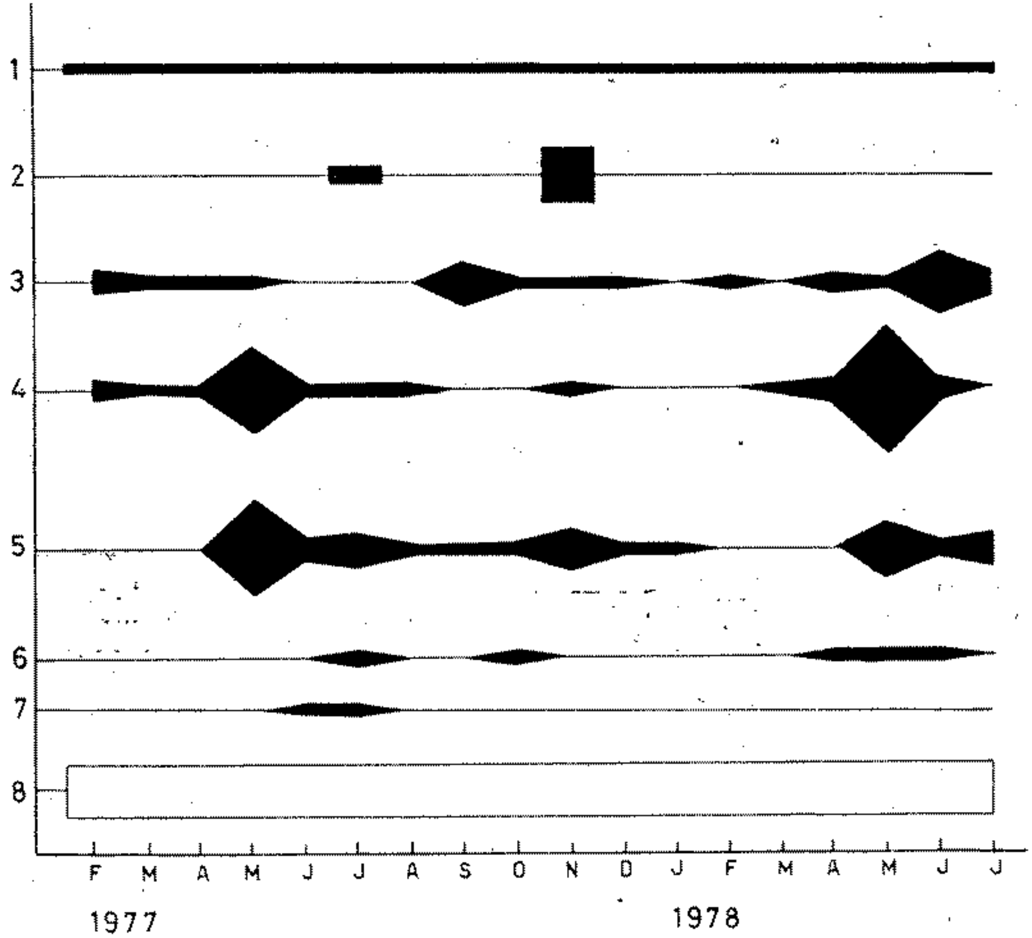

FIG. 5.—Settlement rate of the fouling organisms at Suez station. Ordinates are proportional to the values of the settlement estimated to take place per panel per month: 1) Algae. 2) Hydroids. 3) Serpulids. 4) *Bugula neritina*. 5) Encrusting Bryozoa. 6) Barnacles. 7) Ascidians. 8) Silt which is included to illustrate its role in this station.

pier of each station starting from May 1977 up to the end of the whole work. Monthly sampling from these stations was made in an alternative way, i.e., from a station in a month and from the following one in the next month. In other words, each exposure set of panels was submerged for two successive months. Unfortunately some of these sets were lost but samples representing the pier fouling was then collected to recognize the prevailing communities in the location. However, since such pier collections are not quantitative they have not been shown in the corresponding figures.

Alongside with each collection sea water temperature was measured and in any day the difference between the maximum and minimum sea water temperature rarely exceeded 3° C (Table 1) and this could only be accorded to day-time of measuring of temperature.

Light intensity in air, and in water 5 cm below the sea surface, were recorded by a Luxmeter during the collection time and Figure 2 shows the maximum and minimum ratios betwen the two intensities in 13 locations. The figure reveals that in Port Said and Ismailia least transparency occurs and in the southern part of the waterway turbidity is higher than in the northern part. In May 1978, the light

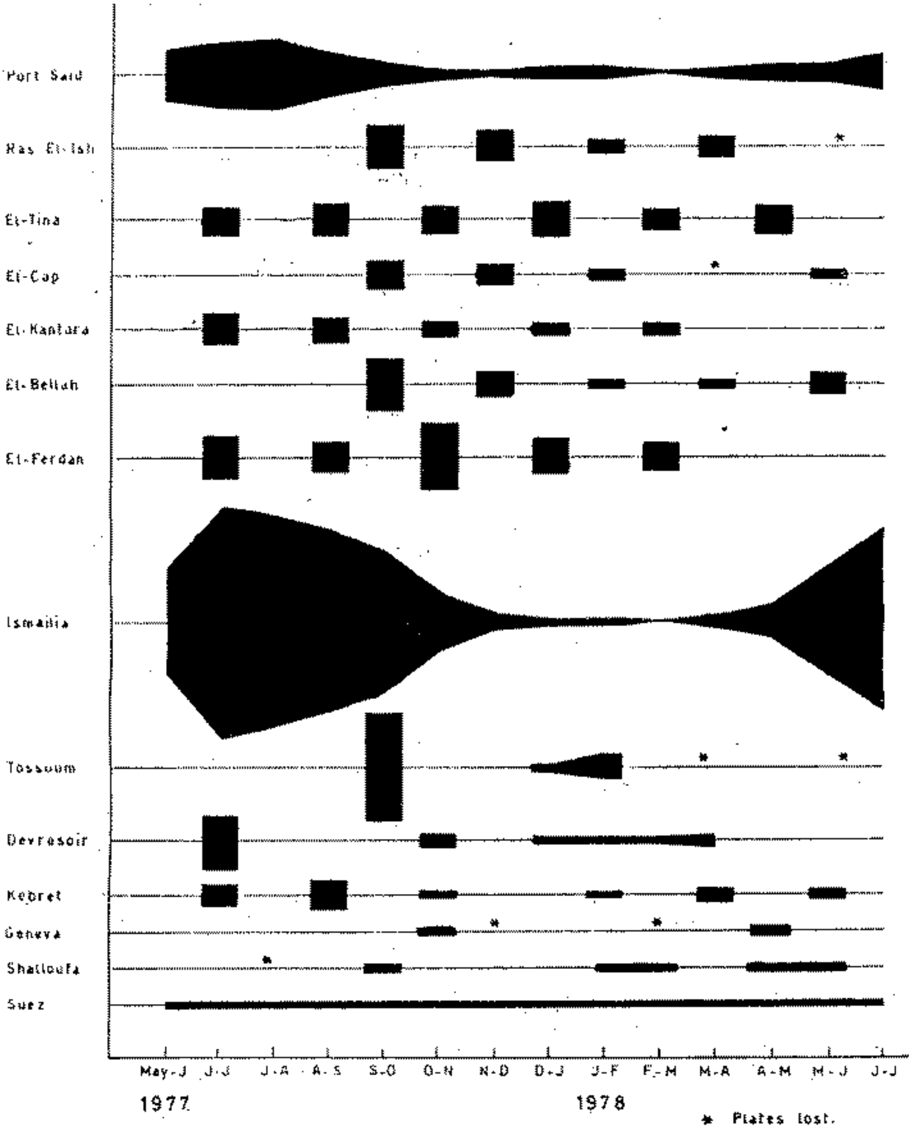

FIG. 6

FIG. 6.—Wet weights of fouling estimated to be collected by a panel immersed in each station for two successive months showns as ordinates.

intensity above the sea surface in Port Said was 74 × 10³ lux and at 5 cm below the sea surface was 5 × 10³ lux while they were 65 × 10³ and 22 × 10² lux in Ismailia and 60 × 10³ and 15 × 10³ lux in Suez, respectively.

Figures 3, 4 and 5 represent the amount of the principal foulers settled on a surface of a panel (12.5 × 12.5 cm) exposed successively for 30 days from January 1977 to July 1978. Because of the high intensity of fouling in Port Said and Ismailia the width of each histogram illustrates the square root of the total number settled during the corresponding

TABLE 1

TEMPERATURE RANGES OF SEA WATER IN THE CANAL

	Minimum	*Maximum*
Jan.	16	16
Feb.	16	18
March	16.5	18.5
April	20	22
May	22	26
June	26	23
July	27	31
Aug.	28	31
Sept.	26	29
Oct.	24	25.5
Nov.	19	22
Dec.	16	16.5

month. Wet weight of fouling growths per panel (the two surfaces) per 60 days in the fourteen investigated locations are shown in figure 6.

RESULTS

I. CONSTITUTION OF THE SETTLING COMMUNITIES

The fouling communities prevailing along the Canal consist in their majority of algae, sponges, coelentrata, bryozòa, polychaeta, crustacea, mollusca and ascidiacea. Table 2 shows a comparison between the density of settlement on the exposed panels in the stations during the four seasons. The forms constituing each group will be dealt with in the following account.

Algae

Several algal forms are present in the Canal. However, the most prevailing forms on the submerged surfaces were these: *Ulva facia, U. lactuca, Enteromorpha intestinalis, E. compressa, Cheatomorpha sp., Calothrix sp., Cladophora sp., Lyngbya sp., Ectocarpus sp., Sargassum sp., Ceramium rubrum, Acrosymphyton sp.* and *Polysiphonia.*

The green forms are the most common and appeared throughout the Canal at least as films covering test panels. In general, the plant growths predominated only when the animal fouling was relatively scarce when it was cold and in the region south to the Bitter lakes. Nevertheless *Ulva* blades were numerous and about 8 cm long on Port Said exposures during June and August 1977. Dominance of this genus in Port Said and Ras El Ish contrasts with its scarcity in Ismailia and its disappearance in all southern stations. In contrast, settlement of *Enteromorpha, Chaetomorpha* and *Cladophora* as well as the brown forms takes place in winter in Ismailia and its surrounding stations. *Polysiphonia,* the only identified red form, flourishes south to Ismailia particularly at Devresoir.

Sponges

They have never been encountered on the test panels. Few colonies of *Leucosolenia sp.* were, however, found on piers at Port Said, El Tina, Tossoum and Devresoir during February 1977.

Coelentrata

The hydroids spread markedly along the Canal from Port Said to Suez. The colonies sampled belong to *Tubularia larynx, Tubularia sp., Obelia geniculata, O. dichotoma, Eudendrium sp., Plumularia sp., Bougainvilla sp., Campanularia sp., Clava sp.* and *Coryne sp.*

Except for Ismailia and Tossoum the tubularians were the leading hydroids if the density of settlement is regarded. Huge number of polyps, mature and about 9 cm long, exclusively dominated the northern region exposures (Ras El Ish - El Ferdan) particularly in winter and spring months. Southern to Tossoum (Devresoir - Suez) colonies mainly belonging to the unidentified *Tubularia sp.,* were leading the fouling there. Settlement of *Obelia,* which comes next to *Tubularia,* is more severe in Devresoir and Kebret than in other stations, but the hydrocauli were in the majority immature and were always less than 10 mm high. The other hydroids, lead by *Eudendrium*

TABLE 2

Distribution of fouling organisms along the Suez canal in winter (W), spring (Sp), summer (S) and autumn (A).
(::) abundant, (+++) common, (++) frequent and (+) rare.

Species	Port Said				Ras El-Esh				El-Tina				El-Cap				El-Kantara				El-Ballah				El-Ferdan				Ismailia				Tossoum				Devresoir				Kabret				Geneva				Shalloufa				Suez			
	W	Sp	S	A	W	Sp	S*	A	W	Sp	S	A	W	Sp	S*	A	W	Sp	S	A	W	Sp	S	A	W	Sp	S	A	W	Sp	S	A	W	Sp*	S*	A	W	Sp	S	A	W	Sp	S	A*	W*	Sp	S*	A	W*	Sp	S	A	W	Sp	S	A
Algae																																																								
Ulva sp.		+	+++		+++	+										+	++													+																										
Enteromorpha sp.													++			+					::								+	+			+++																							
Chaetomorpha sp.																	++					::				++	++		+																											
Calothrix sp.													+++																																											
Cladophora sp																																	+++																			+++				
Lyngbya sp.	::																																																							
Ectocarpus sp																+			+		++				+					+								::				+											+			
Sargassum sp.																																								++																
Ceramium rubrum																+								+																																
Acrosymphyton sp.																+																																								
Polysiphonia sp.																			+														+				+	++	+	+													+			+
Algal films	++	+	+	::						+++															++				++			+					+				+++												+		+	+
Sponges*																																																								
Leucosolenia sp.	+								++																								+				+																			
Coelenterates																																																								
Tubularia sp.	+	+			+++	::	+		+++	::	++		+++	+			::	+++	++		++				+	+	++										+++	++	++	++		++	++			++		++		+						++
Obelia sp.	::							+			+	::				+				+										+	+						::	++		+		++	++	+++											++	
Eudendrium sp.			++	++			+	+																+							+												+	+								+				
Plumularia sp.						+													+++	++							+++	++																												
Bougainvillia sp					+++																																																			
Campanularia sp.								+					+																																											
Clava sp.																																+																								
[illegible] sp.																															+								+																	
Ophiactis sp.								+			++	+++	+			+			++	+							++				+		+																							
Polychaeta																																																								
Hydroides elegans	++	::	::	::	++	+	+++	++	++	+	+	+	++	+		+	+		++	++	++	++	::	++	+	++	+++	+++	++	::	::	++	++			+	+	+	+++	+		+	+	+		+							+	+		
Serpula sp.		++	++		++																									+	+	+						+															+			
Spirorbis sp.			+																								+					+																					+			+
Bispira sp.																			+	+																																				
Pomatoceros triqueter			++								+																					+																								
Dasychone lucullana			+				+	+											++										+		+	+				+			+					+												
Terebellides sp.																															+																									
Polydora sp.																																																								
Bryozoa																																																								
Bugula neritina	+++	::	+++	+		::	+++	::		+	+	+	+					++	++		+			++	+				++	+	+	+	::			+	+	++	+			++	++	+		+			+				+	+	+	
" turbinata	+++	+++	+		+++	++			+											+	+				+				++	+	+	+	+				+																			
Bowerbankia sp.								+			++													+					+								++																			
Schizoporella unicornis				+					++			+									+++			+	+									++								+	+	+											+	
" errata			+								++																						+				+		+																	+
Scrupocellaria sp.																																										+++	+++	+++												
Watersipora cucullata																																						++				+	+												+	
Mucronella aegyptiaca																																											+	+												
Cryptosula sp.																																						+						+											+	
Electra pilosa																																						+					+													
Corbopora dumerili			+																																		+																			+
Membranipora membranacea				++					+		++	+									+																																			
Aetea sp.		+																																																						
Encrusting colonies																																											+	+						+			+			++
Crustacea																																																								
Balanus amphitrite	+	::	++	+++	+		+	++	++		+++	::	+	+		::	+	+	+	+	+	+	::	++			++	+	+	+	+++	+++	++			+	+	+	++			+	+++	+				+	+	+				+	+	
" eburneus	+	::	+	+	++				+		+	+++	+			+++		+	+	+	+			+			++			+	::	+++	++			+			+									+	+	+				+		
" trigonus	+	+	++	+					++											+																																				
" perforatus	+	+	+																																																					
" improvisus				++							++		+								+																																			
Jassa falcata													+++																																											
Corophium sp	+	+							+																	++	++	+	++	+++	++	++	++			++	+++	+++	+	+			+	+				+						+		+++
Podocerus sp.																															++	+																								
Amphipoda tubes	+++	::	++	++	+++	+		++		++	++	++	+++			+++		++	+	::	+++	+			::	::	+++	::	+++	::	++	++	::			++	::	::	+				+	+												
Mollusca																																																								
Anomia ephippium			++		+			+			+		+						+	+		+	+	+			+	+			+	+							+				+													
Brachidontes sp.																													+		+	+	+			+++								++			++		++							
Musculus sp.																								+							+++																									
Ododera sp.																													+																											
Ascidians																																																								
Ciona intestinalis	+++	+																											+++	+++																										
Ascidia mentula								+											+					+			+++				+					++			+	+																
" obliqua			+																																																					
" nigra																											+	+			+					+																				
" virginea																																							+																	
Phallusia mammillata																															+																									
Diplosoma listerianum			+++	+			+	+		+	++								::	++				+++			+++			+	+++	++			++				::																	
Didemnum candidum			+					+											+					+			++						++		++	+++			+++																	
Distomus variolosus	+		+	+						+	++								+++					++			++		+		++	::			++	::			+																	
Polyclinum aurantium			++		++	++					+	+							+					++			++				+				++	++			+																	
Styela partita			++					++		++	++		+						++	++							++				+	++	++		++	+			+															+	+	
Perophora sp.																			+++													+			++	++																				
Botryllus schlosseri			+																								+++				+++	+			++	++			+++																	
Botrylloides leachi																											++	++							++																					
Clavelina sp.																																												+++												
Compound ascidium				++		+++					++	+							+	+														+	++																			+	+	

(*) No data collected
(*) Field observations

(W) December, January and February
(Sp) March, April and May

(S) June, July and August
(A) September, October and November

whose colonies crowded during summer and early autumn in Port Said and other stations (Table 2) appeared sparsely in few stations.

Single actiniarian form identified as *Ophiactis sp.* formed populations varying from few specimens on some panels to about 200 specimens on others suspended in El Tina during September-October period. This sea anemone did not exceed 1 cm in height and 0.5 cm in width. Many specimens were found occupying the interior of perishing acorn barnacles. Settlement of the anemones has been confined

Settlement of the anemones has been confined to the stations from Ras El Ish to Tossoum.

Polychaeta

Both sedentary and errantic polychaetes predominate among fouling growths. The sedentarians lead by the serpulids particularly *Hydroides elegans,* contain *Serpula vermicularis, Vermiliopsis infundibulum, Pomatoceros triquiter, Bispira sp., Spirorbis sp., Dasychone lucullana, Poydora ciliata* and *Terebellus sp.* Among the errantians met with in the fouling collections are *Nereis sp., Lepidonotus sp., Glycera sp.* and *Syllis sp.*

Almost all panels investigated were collecting tube worms varying from about 5 worms for Suez station panels to over 10,000 worms per panel in Ismailia during April, May and June exposures in 1977 and 1978. Figures 3 and 4 show that these serpulids are abundant in Port Said and Ismailia in the majority of the year, except in February and March. They are not so abundant neither in the intermediate stations nor in the southern stations. *Serpula* settled with *Hydroides* on many panels and few *Pomotoceros* worms as well as worms of *Spirorbis* settled in Port Said and Ismailia during August and October-November, respectively. *Pomatoceros* was also encountered in El Tina in August-September period and *Spirorbis* in Suez from October to February. The sabellid *Dasychone* has lead the nonserpulids but did not occur south to Devresoir and its peak settlement was reached during July in Port Said, El Tina, El Kantara and Ismailia.

Bryozoa

Although the erect forms dominate the sea mats along the majority of the Canal (from Port Said to Devresoir), settlement of the encrusting species is more outstanding in the stations south to Devresoir.

Bugula neritina is the principal bryozoan species in the Suez Canal and comes next to it the other erect form *B. turbinata.* The other forms appeared occasionally in varying quantities on the test panels. These forms are: *Atea sp., Bowerbankia sp., Schizoporella unicornis, S. errata, Watersipora cucullata, Callopora dumerili, Membranipora membranacea, Electra pilosa, Scrubocellaria sp., Mucronella egyptiaca, Cryptosula sp.* The genus of some encrusting colonies found in the southern region could not be determined due to the silting of their surfaces. Season of settlement of both species of *Bugula* was longer and their colonies were also markedly more abundant in Port Said and Ras El Ish than in the majority of Canal locations. March-April, 1978 panels of Kebret collected 135 colonies of *Scrupocellaria* which made up about 50 % of the fouling of these surfaces.

Bowerbankia, the only stolonate form in the collections appeared in El Tina largely in June-July 1978 and in fewer quantities during September-October in Ras El Ish, El Bellah and Tossoum.

The most often encountered encrusting species in the northern part of the Canal is *Schizoporella unicornis;* its colonies constituted about 40 % of the fouling of El Bellah in December.

The accumulation of the bryozoans in Kebret exceeded, in number, all that found in any other single station (Table 2). During June-July time 60 colonies of *Scrupocellaria* covered 30 % of the panel surfaces and as indicated above 50 of the panel areas were occupied by its colonies during March and April 1978.

Crustacea

The representatives of this class on the test panels belonged to subclass Cirripedia (acron barnacles), order Amphipoda, order Isopoda and order Decapoda (*Caridea* and *Brachyura*).

The most common barnacles in the Suez Canal are *Balanus amphitrite,* var. *denticulata,* and *B. eburneus* but in Port Said as well as in few stations south to it, in addition to these two species there occur *Balanus trigonus, B. perforatus* and *B. improvisus.* Tubes formed by the amphipods *Corophium sp., Jassa falcata, Podoceros sp.* and by others frequently encrusted heavily panels immersed in the majority of the Canal, particularly in Ismailia and its neighbouring stations. Their increase was observed to occur side by side with that of the barnacles. Other amphipods were also found in varying quantities in samples, among them were *Gammarus sp., Orchestia sp., Amphithoe sp., Stenothes sp., Elasmopis sp., Caprella sp.* and *Themisto sp.* Many isopods were found inhabiting dead barnacles settling at Port Said as well as at some other northern stations. The isopods collected and identified are *Sphaeroma sp., S. malkari, Cirolana sp., Limnoria sp., Idotea neglecta* and *I. emarginata.* Few individuals of portunid and xanthid crabs, of alphid shrimps were observed in samples. Picnogonids were also present.

Two peaks for the settlement of barnacles, lead by *Balanus amphitrite* took place at Port Said one during spring (March-April) when there was about 3000 specimens/panel and the other during autumn (October-November) when there was about 200 specimens/panel. While *B. trigonus* outnumbered the other species in August, *B. perforatus,* represented by specimens not exceeding 20/panel, was the least settling barnacle in this harbour during this work.

Balanus eburneus outnumbered *B. amphitrite* on Ismailia panels and there both largely settled from July to September. July panels in both years, were wholey occupied by over 800 specimens forming three layers, those in the lowermost layer had the largest size (about 12 mm in rostro-carinal length). South to Ismailia barnacle settlement was greatly reduced and no definite season has been observed.

Mollusca

The bivalves *Anomia ephippium, Brachiodontes sp., Musculus sp.* frequently settled on panels and only a single specimen of the gastropod *Diodora* was found on a panel exposed during January-February 1978 at Ismailia.

Despite being comparatively few *Anomia* was the most often encountered on panels north to Ismailia. *Brachiodontes* which grows vigorously on the shores of the Bitter lakes, as well as on the shores of Geneva and El Shalloufa, 300 specimens of it were found on a panel collected from Tossoum in October. This bivalve has never been encountered northern to Ismailia. Settlement of *Musculus* was mainly observed in Ismailia, and on a panel surface exposed during July 1977, 100 specimens of it were counted.

Ascidiacea

Fouling of these urochordates was severe in summer, throughout the Canal, except south to Devresoir. *Ciona intestinalis* was the only thriving ascidian during winter and appeared only at Port Said and Ismailia. In addition to *Ciona* the community comprised *Ascidia mentula, A. obliqua, A. virginea, Phallusia mammillata, Styela partita, Distomus variolosus, Perophora sp., Clavellina lepadiformis, Diplosoma listerianum, Didemnum candidum, Polyclinum aurantium, Botryllus schlosseri* and *Botrylloides leechii.*

Distomus, Diplosoma and *Didemnun* are the chiefly settling ascidians and the populations formed by them in addition to others were greater at Ismailia and Tossoum than in the other areas. Their flourishing growths appeared on the piers of the station from El Kantara to Devresoir from June to November and overwhelmingly from July to September. During this period larvated colonies of *Diplosoma* and *Distomus* occupied 30-70 % of the panels area. *S. partita* was also frequently encountered and on panels collected from Tossoum in October, there were 30 individuals, each about 1 cm long, of this solitary ascidian. *Clavellina* represented by about 135 colonies per panel for September exposures were the only ascidians collected from Kebret.

II. FOULING CHARACTERISTICS OF THE STATIONS

Port Said

Figure 6 shows that settlement of fouling organisms in Port Said attained its greatest rate on both sides of a panel exposed for 60 days during July and August 1977 (188 g). Such figure put this station, among the fourteen Canal stations, the third with respect to the density of fouling. Furthermore, a panel surface exposed for 30 days collected fouling in these two months heavier than that collected in any other month (50 g in July and 47 g in August). In contrast, December-March period presented the least settlement; in any month of these a panel surface failed to collect more than 10 g of fouling.

The fouling picture outlined by Figure 3 illustrates continuous settlement of the tube worms, barnacles, amphipoda tube and *Bugula neritina* throughout the year. Abundance of the tube worms, mainly represented by *Hydroides*, was observed to occur from May to December and over 2000 worms occupied the surfaces of the panels exposed during May and June 1977. Port Said is unique in having barnacle community represented by 5 species lead by *B. amphitrite* and *B. eburneus* from which about 3600 minute specimens/panel appeared in March 1978. Maximum settlement of *B. trigonus* happened when more than 100 specimens per panel were found in August. February, March and April of the two years were the months of peak settlement of *Bugula neritina* and there were from 140 to 280 colonies of this bryozoan per panel in each of these months. *B. turbinata* was also flourishing in these months.

A list of the intermittent settlers contains *Obelia geniculata* in January and February, few colonies of *Tubularia*, in December, January and in May, *Ciona* which vanished when the other ascidians fluorished and many other organisms is given in Table 2.

Growth rates of tube worms and barnacles were relatively small because the formers were always shorter compared with those settled in the same time in Ismailia, while barnacles found on any panel rarely exceeded 10 mm in the rostro-carinal length.

It is worthy to mention that the fouling density during 1978 was less than that found in the year before. Nevertheless, the settlement pattern of the principal foulers was nearly the same in the two years.

Ras El Ish

Adjacence of this station to Port Said makes it more influenced, as regard the fouling quality, by this harbour rather than by any other Canal location. Like Port Said *B. neritina* was so enormous that it cannot be compared with any southern station. 60-90 % of the surface area of autumn and spring panels were occupied by more than 250 colonies of this species. *Ulva* also was the only algal representative and covered a large area of panels from January to April. However, being on the waterway the stations south to it affected its fouling both qualitatively and quantitatively. Hydroid fouling, compared with Port Said, is large and is formed of greater number of species. *Tubularia* colonies increased and in March-April exposures they covered 60 % of the offered surfaces and their polyps reached 8 cm in height. Sea anemones which were not found at Port Said appeared but rarely in this station. Barnacles were few and from September to April no panel immersed for two successive months collected more than 50 specimens. Ascidians were apparently confined to summer and *Styela partita, Polyclinum* and *Diplosoma* lead, in settlement, the sea squirts.

Minimum fouling density took place in January-February (37 g/panel/60 days) while the maximum density was observed in September-October and reached 108 g/panel/60 days.

El Tina

This station is characterised by having a long season, from December to June, dominated by *Tubularia*. Severe settlement of this hydroid took place in spring, and in March mature polyps, about 9 cm long, covered about 40 % of the panels areas. Barnacle season starting in June, dominated in November-December to the extent that 100 % of the panel surfaces were occupied with thousands of developing individuals and diminished after January. In addition to *B. amphitrite* and *B. eburneus*, there were about 35 specimens of *B. trigonus* settled per panel during December-January period. Well grown barnacles were found dead in September and were invaded by sea anemones which settled then in comparatively large quantities (about 200 specimens/panel). *Bugula*, tube worms and ascidians were uncommon in this location. The rate of settlement did not change greatly and ranged between 58 g/panel in February-March and 94 g/panel in December-January.

El Cap

Although less dense, *Tubularia* growth continued for a period nearly as long as that occurring at El Tina. More than 5000 specimens of *B. amphitrite* and 1000 specimens of *B. eburneus* settled on each panel exposed during September-October period. Peculiarly before and after this period barnacles were scarce. The increasing tube worms and amphipoda tubes occupied 50 % and 40 % of the areas of the panels immersed in November-December duration, respectively. All types of algae flourished during autumn and winter. The standing crop was generally lower than that of El Tina, it reached the minimum in May-June 1979 (20 g/panel) and its maximum was during September-October (83 g/panel).

El Kantara

Like the preceding two stations, especially El Tina, *Tubularia* dominate from December to June. However, ascidians lead by *Diplosoma* and *Distomus* covering more than 70 % of June-July panels and *Plumularia* spreading on 30 % of August-September panels present features unrepresented in the fouling of both El Tina and El Cap. On the other hand, about a quarter of the exposed surfaces was occupied by tube worms during October-November period. Death of small barnacles was also obvious in the locality. Four specimens of *B. trigonus* were observed on a panel suspended during the same period. Heaviest fouling was collected from June-July panels (83 g/panel) and the lightest was collected from the panels during the periods from October to March when its weight never exceeded 30 g/panel/60 days.

El Bellah

Fouling in this location was not only more intensive than in the three stations north to it (standing crop ranged from 135 g to 148 g/panel/60 days in September-October and March-April periods, respectively) but also differed in having *Tubularia* diminished and tube worms, ascidians and amphipodans largely settling. A panel, during September-October, collected 240 specimens of *B. amphitrite*, *Diplosoma* and *Distomus* spreading over 60 % of the exposed surfaces, 20 individuals of *Styela partita*, 300 *Hydroides* worms and few *Musculus* animals. In the six months succeeded flourishing of algae, namely *Enteromorpha compressa*, *Cheatomorpha* and *Ectocarpus* was so great that they extended on about the whole areas of the panels. 14 *B. neritina*, 8 *B. turbinata* and extensive *Schizoporella* colonies in addition to 160 worms of *H. elegans*, thousands of amphipod tubes constituted the settlers on a panel belonging to November-December exposures.

Domination of *Hydroides* and the barnacles during May and June 1978 was so exclusive that they formed the majority of the weight of fouling, 55 g, on each exposed panel.

El Ferdan

Being close to Ismailia its fouling growths were more severe than in any other northern location; the wet weight ranged from 182 g in October-November to 76 g per panel in February-March. The assemblages were more or less analogous to those found at El Kantara. Ascidians, represented by huge colonies of *Diplosoma, Didemnum, Polyclinum, Distomus, Botrylloides, Botryllus*, 6 specimens of *Ascidia nigra* and 52 specimens of *A. mentula* in addition to *Plumularia* colonies and tube worms dominated the fouling of the panels exposed during the periods from June to September. *Tubularia* settlement started in October-November, its large colonies covered 50 % of the panels of the next period and lasted until June. In the same time (from October to June) tubes of amphipods were attached to increasing areas of the substrates. Like El Bellah green and brown algae flourished during October-January months.

Ismailia

The most severe fouling in the Canal takes place in this area and settlement of the bivalves in large quantities emphasizes this severity. A panel collected in 60 days 630 g of fouling, a weight which is greater than the total weight of the fouling of the southern six stations in their maximum settlement seasons. Nevertheless, quite a big range of the fouling density on the fouling surface has occurred, it was 200 g in July 1977 and only 1 g in March 1978.

All marine fouling animals grow abundantly in Ismailia and in some months the exposed sites became exclusively inhabited by a big population of one or two species. For instance, May 1977, May and June 1978 panels were solely occupied by huge growths of the tube worms which attained a density of 5,000-10,000 worms per panel. Barnacles on the other hand, dominated during July 1977 and 1978 but they were more numerous in the first year. During August and September colonial settlement, larvated as well as solitary ascidians, but *Ciona* which flourished only during cold months, became promoted and extended on a great part of the surfaces. More than 25 % of the panel surfaces were occupied by *Diplosoma* and *Distomus* colonies which appeared up to December. 400 barnacles specimens represented more or less equally by *B. eburneus* and *B. amphitrite* dominated again in October. Besides, there were 23 worms of *Pomatoceros* which attachment continued but in fewer numbers in November. Growth of *Bugula* and other bryozoans was reduced and flourished only in February 1977 when 86 colonies of *B. neritina* settled on a panel.

This locality is not only characterised by the severity of settlement but also by the promoted growth rate of the settlers. Within a month of attachment the carino-rostral length of the two barnacle species reached 12 mm and both became mature. *Hydroides* worms also reached remarkable lengths.

Surprisingly, a big drop in the amount of fouling per panel per 30 days occurred from December to May 1978 (10 and 16 g, respectively), but in the year before the weight of panel fouling in May was 26 g/30 days.

Tossoum

This location lies on the southern boundaries of Timsah lake; the biomass of fouling there was greater than in any other station, except in Ismailia's. Moreover, growth of ascidians was so successful that it sweepingly occupied all the offered sites, including the pier, from May to October. On the test panels of September-October there were colonies of *Distomus* attached to 70 % of the areas, huge colonies of *Didemnum, Polyclinum, Botryllus,* large number of well grown *Ascidia mentula, A. nigra* and of *Styela.* On the same panels there were 2 specimens of *Anomia* and 300 specimens of *Brachiodontes* per panel. Few colonies of *Obelia, Bowerbankia, B. neritina* in addition to few of *Hydroides, Sabella, Balanus amphitrite* and *B. eburneus.* There were also some individuals of errantic polychaetes, flat worms, crabs, amphipods and isopods. The weight of such fouling was for a panel 287 g/60 days but in December-January it became 22 g/panel/60 days when fouling was mainly made up of algae and a few animals.

Unfortunately, the pier of the station has been destroyed in March 1978 in order to facilitate the widening of the Canal in the area, which prevented further sampling.

Devresoir

This station is built on the northern entrance of the Great Bitter lakes and as a southern station it comes next to Tossoum with respect to the severity of fouling. The ascidians were also dominating, and a panel fouled during June-July 1977 had had its surface divided as follows: 70 % *Diplosoma,* 15 % *Didemnum,* 10 % *Botryllus* and on the rest of it there were *Distomus, Polyclinum, Ascidia mentula, A. virginea,* about 1000 *Hydroides* worms, 76 specimens of *Balanus amphitrite,* 10 immature *Bugula neritina* colonies and few other organisms. These assemblages of animals weighed 150 g. In contrast to this panel, another suspended in February and March the majority of its fouling consisted of green and red algae, some encrusting colonies of bryozoans, and few tube worms. Its fouling weight was about 1 g only. On panels mounted in other durations *Tubularia* and amphipodans were the main settlers in addition to algae, *Obelia,* tube worms and bryozoans.

Kebret

This is the only pilotage station which is situated on the Bitter lakes. Constitution of fouling assemblages was thus quite different from the stations north and south of it. While bryozoans, especially the encrusting forms as well as bivalves were settling largely; algae, hydroids, tube worms, barnacles and ascidians were not common. The bryozoans settlement was very distinct throughout the year without clear preference to a definite season. The main settlers were *Scrupocellaria* which was represented during June-July and August-September 1977 by extensive 60 colonies and 52 colonies per panel respectively. *Schizoporella* which was represented on each test panel by at least 5 colonies, and, on May-June 1978 panels, there were 62 colonies per panel. *Bugula* was also frequently settling, but *Bugula neritina* which was continuously represented by few colonies not exceeding 20 colonies/panel. *Scrupocellaria* was represented on March-April 1978 by 135 colonies/panel attached to about 50 % of the panel areas. The community included *Watersipora, Electra, Mu-*

cronella and *Bowerbankia*. *Brachiodontes* and *Anomia* which are common on the Bitter lakes settled frequently on the panels.

The standing crop ranged between 83 g/panel/30 days in August-September to less than 1 g during the period from October to February when in some durations panels were found entirely devoid of fouling attachments.

Geneva, El Shalloufa and Suez

These stations which are located on the Canal extending from the southern border of the Bitter lakes to the Suez Gulf represent the least fouled section in the waterway. Figure 6 shows that the total fouling occurring in them is less than half that occurring in any single location in any month.

No definite settlement season could be recorded for any animal or even for a group of animals. On the contrary, settlement of silt on the panels was steady and much greater than that of the organisms. Almost all fouler groups appearing in the other Canal stations were represented in this section, but in very small amounts and in minute sizes never encountered as such in any other stations. For instance, the barnacles and the tube worms never exceeded 1-2 mm in length, *Bugula* colonies were always made up of two or three branches, and the encrusting bryozoa and ascidians although not similarly few, they were too small in size that they could not be identified. *Tubularia* growths were more distinct than the others and reached considerable sizes on a panel immersed in Suez during November 1977.

DISCUSSION

A Canal 162 km long, joined in the north and in the south with two faunally different seas, receiving fresh water in some parts and passing through highly saline water in others is not expected to be uniform when dealing with its fouling communities. However, it might be convenient to elucidate the distribution of fouling and its nature along the Canal. On the basis of the figures obtained for the standing crop of the fourteen investigated stations (see figure 6), the Canal could be divided into 5 sections. The southern most three stations, namely, Suez, El Shalloufa and Geneva constitute the poorest fouled section. Ismailia and the surrounding 4 stations (from Devresoir to El Bellah) represent the richest section in this respect. Port Said and Ras El Ish form a section while Kebret and El Tina-El Kantara, on the other hand, constitute the last two sections.

Agitation caused by the strong wind in the gulf of Suez (Mashal, 1970) accelerated by the swift currents of tides which range between 80 and 140 cm in neap and spring tides, respectively (Morcos, 1970) obviously result into getting silt as the major settler at the Suez-Geneva region. In such a state metamorphosing larvae will be prevented from reaching the attachment sites, and if some succeed, further growth will be smothered. This is truly occurring and no organism can reach a size reached in other Canal regions. However, settlement of large variety of organisms suggests the occurrence of their larval stages in the water, but failure of the adults to reach maturity in the majority of cases is an evidence of having these larvae coming to the area from outside it. On the other hand, the presence of invertebrate larvae in the Suez region is also demonstrated by the heavy attack of the local timber by ship worms and other wood borers (Hassan, 1979). Presumably the settling larvae are not carried among the plankton of the Red sea, because of the poverty of the plankton in this sea (Salah and Tamas, 1970) and the paucity of fouling observed by the senior author (AFAG) in both the Egyptian El Ghardaqua and the Yemenis El Hodaida harbours at the north and south of this sea, respectively. In both harbours a few barnacles were observed and it is not probable that such sparce fouling in the Read sea is able to produce larvae enough to form fouling communities in any Red sea locality. Having at Suez sedentary species similar to those abundant along the Canal, such as the species of *Obelia, Tubularia, Bugula,* barnacles and *Hydroides,* it can be suggested that a southward current in the Canal, claimed by Morcos (1967) and Dowidar (1971) to be no longer going on, is existing. The duration and the properties of such current is out of the scope of the present work.

The water salinity is greater and the silt is less at Kebret than in the three locations south to it and fouling is more frequent there. Having most forms prevailing at Kebret including shelly forms such as encrusting bryozoa, barnacles, tubes worms and molluscs, this can be attributed to the high concentration of $CaCO_3$ in such salted water (Anwar and Abdel Maksoud, 1970).

A Canal, named Ismailia Canal brings some fresh water from the river Nile to lake Timsah which reduces its salinity (Gerges, 1976) and increases the fertility of the lake and consequently phytoplankton and zooplankton flourish (Steemann, 1961). Such plankton-rich water results into fouling flourish not only in Ismailia but also in the whole area bordering it. The northward current (Gerges, 1976) will carry swarms of the released larvae up to Port Said but further than El Kantara the effect is not so marked, seemingly due to the presence of El Bellah by pass (Fig. 1). Such southward fertile current reaches Devresoir on the northern entrance to the Bitter lakes. In these lakes the current bears with it larvae of the organisms endemic to this saline area to the Suez section.

Port Said, on the northern entrance of the Canal, also receives brackish water discharged from lake Manzala through Kabouti Canal. Another centre of fertile water is thus formed at Port Said and a regional source of fouling is eventually originated and a southward current may carry Port Said larvae some distance down in the canal waterway. As a Mediterranean harbour, Port Said fouling assemblages can be compared with that of Alexandria as described by Ghogashy (1976). An eastward current in the Mediterranean (Halim *et al.*, 1967) is responsible for making the antifouling coatings formulations for Port Said more or less similar to those for Alexandria. *Balanus perforatus* and *B. trigonus* which are common in Alexandria (Broch, 1935, and Ghobashy, 1975) are also present in Port Said, but nearly absent in most of the Canal. However, the scarce presence of the latter barnacle in El Tina and El Kantara confirms the occurrence of a current moving to the south. On the other hand, the presence of *Anomia* and *Serpula* in Port Said despite their absence in Alexandria suggests the influence of the Canal on Port Said fouling.

Figure 6 reveals that the maximally attained standing crops in the three locations, El Tina, El Cap and El Kantara, are nearly the same and Table 2 illustrates their embracing the species dominating along the Canal in addition to being the southern limit for the spreading of the organisms (e.g., *Balanus trigonus*) which are only prevailing at Port Said. The section El Tina-El Kantara is thus more influenced than any other part by both the northward flow of larvae mainly originated at Ismailia and by the southward one comming down from Port Said.

According to a publication by the Canal authorities, the speed limit imposed in the waterway varies between 13 and 14 km per hour. At such speed algae like *Enteromorpha*, which is thriving at a distant part of the Canal, are capable of making a successful attachment to ship hulls (Christie and Evans, 1975). Therefore, it is expected that a traversing ship will be fouled by algae even while steadily moving in the Canal at any time of the year. It is well known that fouling of a ship by animals takes place, largely, when it is stationary. There are three regions where ships have to stop for several hours before resuming their journeys. These regions are Port Said, the Bitter lakes and Suez Bay. The only region where no effective infection by fouling is expected to occur is the Suez Bay but in the other two regions the infection may occur particularly with barnacles, tube worms, bryozoans and ascidians. In deed, the ship owners are lucky not to have their ships lyeing-by at Timsah lake, otherwise ships hulls would be heavily infected especially during warm months.

It is certain that the projects going on to widen the Canal in order to admit two-ways passage will bring down the attachment of fouling larvae on the traversing vessels. In this connection, it is worthy to mention that the turbulence in the waterway caused by the work in these projects has resulted into a general decrease in the fouling intensity during the second year of our collection.

As demonstrated by grab collections throughout the same 14 stations investigated for the present work, living organisms are very scarce on the bottom and the fauna there consist mainly of mollusc shells. Such scarcity may be attributed to the sweeping activity of the sailing vessels as well as to the evacuation of the Canal channel from the dangerous remains of the Egyptian-Israili wars. However, the presence of tremendous growths of fouling organisms along the Canal from Port Said to the lakes evidently compensate such poverty of the bottom benthos and raises the fouling production of the Canal. Moreover, productivity of the fouling in the Canal is great because of the abundance of what has been considered by Thorson (1957) as highly productive animals such as the crustaceans (amphipods, isopods, etc.) and polychaetes (tube worms).

Some phenomena concluded from the results of this work would be important in order to throw light on the behaviour of animals principally growing in the Canal. In spite of the thick layers of silt which make the settlement on the Suez region substrates nearly impossible for the majority of the sedentary organisms, a community of the encrusting bryozoa is formed there. Although, like the others, growth to the natural sizes of the colonies is lacking, the capacity of burrowing among the larvae of these animals should be great and further laboratory investigations in this effect is needed. On the other hand, *Tubularia, Obelia, Bugula* and other bryozoans, *Balanus amphitrite, B. eburneus* as well as *Ulva* and *Enteromorpha* and other sedentary forms constitute the principal fouling organisms in the Suez Canal. These forms are similarly largely settling at Alexandria, and their growth rates in the Canal are similar to those found by Ghobashy (1975 and 1976) in Alexandria waters. While salinity in both waters varies, the temperatures in them are more or less similar. This suggests that temperature and not salinity is not only the main controlling agent in the distribution of these wide-spread animals but also in the growth of them. Contrary to *Hydroides* and *Ciona* which settle enormously in the harbours (Port Said and Ismailia), settlement of *Tubularia* is more marked in the waterway than in the harbours. The water of the harbour is more turbid (Fig. 2) and in contrast to the other two genera *Tubularia* prefers to settle at the uppermost and illuminated sites (Ghobashy, 1976; Ghobashy and Selim, 1977, and Pyefinch and Downing, 1949). The turbidity in Port Said and Ismailia waters seems to arise from the stirring up of the bottom by the inflowing fresh water. Such condition apparently supports the formation of the tube-building amphipods (Thorson, 1957) which increase greatly in the Ismailia section.

Surprisingly, the barnacle *Elminius modestus* which is, as mentioned in the introduction, an immigrant species form Australia, probably, throughout the Suez Canal, to Europe seas (Crisp, 1958) is entirely absent in the Canal. Thus, it appears that a species that is able to survive the Canal conditions is not necessarily able to reproduce and dwell its waters.

SUMMARY

Test panels were suspended along the Suez Canal to collect fouling periodically quantitatively and qualitatively from 14 locations. From the harbours: Port Said, Ismailia and Suez collection took place monthly but from the pilotage stations; Ras El Ish, El Tina, El Cap, El Kantara, El Bellah, El Ferdan, Devresoir, Kebreta, Geneva and El Shalloufa it took place bimonthly. Green algae (*Ulva* and *Enteromorpha*), hydroids (*Obelia* and *Tubularia*), tube worms (*Hydroides elegans*), barnacles (*Balanus amphitrite* and *B. eburneus*), bryozoa (*Bugula neritina, B. turbinata, Schizoporella* and *Scrupocellaria*) and ascidians (*Ciona, Diplosoma, Distomus, Botryllus, Botrylloides* and *Styela partita*) are the principal fouling organisms in the Canal. Silt covers the objects submerged in Suez-Geneva scetion (the southernmost part of the Canal) and prevents attachment of organisms and hence this part is the poorest fouled region. Ismailia waters are not only the highly fouled region of the Canal but it is in addition to Port Said the main source of fouling and from these harbours the fouling organisms propagate throughout the Canal. It has been shown that beside the northward current admitted before by many authors, there should be a southward current originating at Port Said and Ismailia which is responsible for bringing larvae to settle in the Suez region. The traversing vessels are liable to be fouled in the Canal by algae even when in move in the Canal but become fouled by animals when stationed particularly in the lakes.

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NOTES ON THE WOOD BORING IN THE SUEZ CANAL

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ABSTRACT

Five kinds of widely used Egyptian timbers: Labkh, Mahogany, White-Oak, Pine and Peach were exposed, for various periods in the Suez Canal, to find out their resistance to marine wood borers. The bivalved *Teredo navalis* L. and the amphipod *Chelura terebrans* Philippi were recorded in the burrows of the tested wooden pieces. Pine was used as a control and it was found to be more resistant thant other woods. Considering the degree of resistance, Labkh is the lowest while Peach is the highest. Infection increases southward in the Canal and at Suez the damage is very severe.

INTRODUCTION

Wood has long been used for building wharves, boats, piers as well as other marine installations. When exposed to marine borers, wooden structures become subjected to severe damage particularly in subtropical and tropical regions (Southwell and Bultman, 1971). These borers include molluscs (bivalves) and crustaceans (isopods and amphipods) which unfailingly excavate wood and frequently transform it to a wreckage. Galler (1969) quoted that damage caused by these organisms in United States of America alone may average 200 to 250 millions dollars annually.

In October 1977 the first author (A.F.A.G.) and a team of researchers found wooden plates to which fouling test panels were fixed in a collapse due to being tremendously burrowed by boring organisms. Most of the burrows were lined with calcareous sheath which indicated that tredenids have caused such burrows (Turner, 1971). On the complaints of the Suez Canal authorities, it became necessary to study the wood boring problem in the Canal.

This paper explains the work started with as the first step to treat the problem and its aim is to estimate the hazards of wood boring in this international water-way, to test the resistance of some local timbers and to identify the principally prevailing wood-boring organisms.

MATERIALS AND METHODS

Five types of widely used timbers: Labkh, Mahogany (*Swietenia macrophylla*), White-Oak (*Quercus sp.*), Pine (*Pinus sp.*) and Peach were used to compare their resistance to borers in the three main regions of the Canal: Port Said, Ismailia (lake Timsah) and Suez. At each region, two iron frames each bearing 10 pieces of wood arranged in two rows were

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suspended 50-60 cm under the sea surface, from the raft used for fouling studies (see Abdel Malek and Ghanem, 1975). Thus four replicates for each timber were exposed simultaneously in each region.

As Pine is known as a low-resistance wood (Southwell and Bultman, 1971), it was used in another test as a control and as a collector for wood borers for identification. Six frames similar to the others, each carrying 12 pieces of Pine wood were immsersed in the three regions, two in ach region.

All frames were of the same size 100 × × 50 cm, and the wood pieces 16 × 7.5 × × 2.5 cm each.

The work started in June 1978 and during monthly inspection fouling growths were removed and wood condition was investigated in the laboratory in November and in January 1979. Evaluation of the infection was done by counting the holes caused on the timber surface by borers. A timber has been considered severely attacked if the number of the holes on a piece surface of it (16 × 7.5 cm) exceeded 80. Less than 20 holes/surface is considered slight, and between 20 and 80 holes/surface has been rated moderate. Stereomicroscope served to count the number of borers in the laboratory.

Salinity was monthly measured in the place of exposure and its means during 1978 were 38.56 per 1000 in Port Said, 36.04 per 1000 in Ismailia and 43.01 per 1000 in Suez. Salinity ranges in Port Said and Suez were limited and varied in the former region between 37.08 per 1000 in January and 40.16 per 1000 in May and the latter between 42.18 per 1000 in March and 44.99 per 1000 in September. In the lake Timsah discharge of fresh water from Ismailia canal lowered the salinity which reached 25.03 per 1000 in February.

Temperature was nearly the same along the water-way in any day and attained 29-39° C in summer, 19-26° C in spring and autumn and 16-18° C in winter.

RESULTS

WOOD BORERS RECORDED

Although the isopods *Sphaeroma walkari* Stebbing and *Cymodoce sp.* were always found among fouling organisms particularly inside dead barnacles (Ghobashy, El Komy and Ramadan, 1979), they were never encountered in the timber burrows. This may be due to the feeding of these animals, as they do not feed on wood but they attack wood to use it as a shelter (Rayner, 1975). Seemingly, they found barnacles a better shelter after evacuating the shell, probably, by devouring the living matter.

Beside the bacteria and fungi which caused much decay to the wood surfaces, two boring macroorganisms were found; the first is the bivalved mollusc *Teredo navalis* L. and the other is the amphipod crustacean *Chelura terebrans* Phillippi.

Teredo holes on the wood surface were recognized by having a diameter about 1.0 mm wide and by their calcareously lined channels which were noticed throughout most of the wood pieces thicknesses. Diameter of this worm in the upper 4.5 mm pieces depth was often thin, 1-2 mm. Its burrow were elongated and many of them were 3, 4, 5 and 6 mm wide and the largest was 95 mm. As known the internal ends of the tredenid channels are commonly opened (Turner, 1971) because they usually do not stop devouring wood, but in a very few cases channels were clogged. Youngs attaining 13, 18 and 19 mm in length were noticed and older worms; 33 mm long were also collected. And the largest individual obtained from Pine wood was 54 mm long.

Teredo navalis is characterised by the shape of its ridgeless pallets (Turner, 1971), and according to Rayner (1975) the Mediterranean sea is the centre of its occurrence.

Chelura, on the other hand, failed to excavate timber deeper than 4-5 mm of its thickness. Their borers are minute; much less than 1 mm in diameter, and their channels were

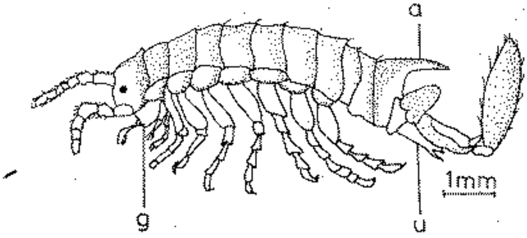

FIG. 1.—*Chelura terebrans.* a: abdomenel segment, g: 1st gnathopod, u: uropod.

narrow and irregularly twisted. The adults and young reached 8 and 4 mm in lengths respectively.

Although Rayner (1975) stated that *Chelura* is usually found associated with the other crustacean borer *Limnoria,* this was entirely disappearing from the investigated timbers. It is more probable that her statement is only applicable to *C. insulae* and not the Suez Canal species. Barnard (1965) stated that *C. terebrans* and not *C. insulae* which inhabits Red sea.

Specimens of *Chelura terebrans* can be distinguished from *C. insulae* as illustrated by Kuhne (1971) by the shapes of antennae, 1st gnathopods, pleopods, abdominal segments and uropods (Fig. 1).

BORING ACTIVITY IN THE SUEZ CANAL REGIONS

In this account a description for the conditions of the timbers exposed in three regions; Port Said, Ismailia and Suez for the durations: June-November 1978, November-January and November-March 1979 is given. In fact most exposure timbers were more attacked near the corners and the holes through which the wood pieces were tied to the frame.

PORT SAID

Least attack to the timbers occurs in this region. During the exposure durations, the bores made up by the marine organisms could be detected and counted. This suggests that surface decay by bacteria and fungi was often not very great.

June-November: Labkh was the most susceptible timber for boring, but its infection was moderate, as only 32 very fine bores were counted on its surface. Reduction in the number of bores on the Mahogany and White-Oak was marked. In the case of Peach and Pine, the activity of borers reached the least degree, and only two holes were recorded on each surface.

November-January: Being the most vulnerable timber, Labkh was burrowed by about 50 holes on each surface. Borers were less active on the surfaces of Mahogany pieces because each of these were attacked in about 40 positions. White-Oak, Pine and Peach were the most resistant woods and the rate of attack was 30-20 holes on a surface.

Investigation of the Pine pieces which served as controls, showed that the attack was very slight (2 bores/surface) and when pieces were broken no damage was observed and the timber was still durable. Extension of the same test until March 1979 did not increase the attack, but it stayed more or less similar to that happened during November-January period.

ISMAILIA

The attack in the lake Timsah, where the salinity reaches the lowest degree, was always greater than in Port Said. Abundant microorganisms worked on the timber surfaces and made it difficult to determine the boring positions.

June-November: White-Oak was the weakest timber in this region and the rate of infection attained 86 bores/surface. Labkh and Mahogany, despite of being extensively acted upon by bacteria and fungi to the extent that it was difficult to define the positions of the borer settlement precisely, their degree of infestation was considered the second after that of White-Oak. Regarding Peach and Pine each surface of them received, in average, 12 and 7 attacks respectively.

November-January: Deterioration of the external surface of the wood due to the severe attack by the microorganisms prevented counting the number of the holes drilled by borers exactly. However, elongated channels were observed underneath these decayed surfaces. Labkh surfaces were imprignated by about 50 holes per each and these holes could be determined in all pieces.

For the Pine test the attack was moderate and about 28 fine holes were found on each surface during this period. From January to March the additional surface boring was only represented by seven holes per surface.

SUEZ

Wood boring in this region was very highly active and the burrows made by the organisms outnumbered those took place in the other two northern regions.

June-November: Labkh was considered to the most severely attacked timber, as 120 holes/surface were counted on its pieces. Pine and Peach were the second and the third in this effect; they were burrowed in 115 and 105 positions in each surface respectively. Finally, both the Mahogany and White-Oak pieces were moderately infected and the number of bores per surface were 50 in the former and 25 in the latter.

November-January: Labkh was still the most vulnerable timber for boring in the Suez area. The infection rate was about 180 holes/surface mainly leading into *Teredo* channels. Both Pine and Peach were severely attacked and the external surfaces of each board were sculptured by many elongated channels. Wood texture became spongy-like due to the intensive boring. Few *Chelura* specimens were easily picked by a needle from narrow grooves in the wood. Attacks on White-Oak and Mahogany were moderate because the number of holes ranged for both between 50 and 55 for each surface.

About 150 bores/surface were clear on Pine exposed alone in the same period. From January to March, further damage was limited and about 20 holes were dug on each surface.

DISCUSSION

The foregoing makes it clear that wood boring in the Suez Canal is notable severe and its serious consequences will certainly endanger the many wooden structures therein. Within a relatively very short time immersed wood of widely used types were attacked with various borers and some was so severely infected that it became practically unuseful. The canal is rich in the phytoplanktons (Dowidar, 1976) which according to Daniel (1955) are the indispensible requirement for inducing the settlement of the boring organisms on the submerged timber. The five kinds of timber investigated in the present work, which are widely used in the canal wooden structures, proved to be highly liable to damage by borers shortly after immersion. Surprisingly, Pine which was selected as a control has shown more resistance than others. Labkh was, in general, the weakest wood used and Peach as the strongest. It has been also noticed that both components of the couples Mahogany-White-Oak and Pine-Peach were more or less similar to each other in this respect.

During the exposure period November-January the attack was really intense. In these two months the wood was nearly as severely infected as in the preceding five months and Pine timber exposed until March 1979; i.e. for additional two months, its infection was not markedly increased. Sea water temperature in these two months reached the minimum, 19-17.5° C, the best thermal condition for the temperate *Teredo navalis* which was found to release its larvae optimally between 16 and 20° C (Imai, Hatanaka and Sato, 1950, and Loosanoff and Davis, 1963). This species has been also found to settle during the late summer and autumn in Japan and San Francisco Bay (Imai *et al.*, 1950; Scheltema and Truitt, 1956, and Tsunda and Nishimoto, 1972). Seemingly the same species behaves similarly in the Suez Canal. Pits of *Chelura* were also numerous on the wood surfaces during the same two months but the lack of information on its breeding conditions makes it somewhat difficult to draw a parallel conclusion.

Suez leads the other two Suez Canal regions in the respect of the intensity of timber infection by marine borers. Salinity is the highest in Suez waters; it is never below 42 per 1000, but in warm climates, such high salinity should inhibit tredenid settlement (Rayner, 1975). Obviously scarcity of fouling growths at Suez (Ghobashy *et al.*, 1979) gives the borers larvae the best chance to burrow the wood substrata conveniently. Moreover, while the other two localities (Port Said and Ismailia) are nearly tideless, the tide level changes at Suez are marked and the water rises 140 cm at spring tide (Morcos, 1960). Rayner (1975) suggested that there is a link between the tidal fluctuations and the optimum settlement of tredenid larvae.

ACKNOWLEDGEMENTS

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SYNTHESIS AND APPLICATION OF POLYMER-BOUND BIOCIDES WITH ANTIFOULING PROPERTIES

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1. INTRODUCTION

Marine vessels, off-shore oil platforms, in fact all kinds of marine constructions in contact with seawater, are subject to fouling by marine organisms. One way to overcome this undesired effect is to provide the necessary anticorrosive system with an additional coating which slowly releases one or more biocidal substances. These coatings are called antifouling paints.

The oldest and up to now most used toxicant is cuprous oxide. Next to it the use of organometal compounds as toxicants in antifouling paints is steadily increasing. This is due to the fact that they are more effective against algae and barnacles, the main fouling organisms. Especially triorganotin compounds are in the picture because they do not have undesirable properties of other toxicants such as organolead or organomercury compounds. These biocides have the disadvantage to be too toxic to workers producing and applying them. Besides that the latter compounds have a larger impact on the environment, being dangerous for a large number of higher organized organisms.

Investigations into the toxicity of organotin compounds learned TNO (1) that organotins may be less hazardous to workers in the paint industry and in the dock-yards.

Antifouling paints based on a physical mixture of binder and organotin compounds do not last very long. The most conventional organotin-containing systems loose their activity within one to one and a half year. Various authors have claimed that organotin groups chemically anchored to a polymeric backbone give coatings which are longer lasting and are environmentally safer.

Despite recent advances in slow release techniques, only a few reports have been published containing detailed scientific and technical information on the properties of synthetic antifouling polymers (2).

Since TNO has experience in the field of the biological activity of organotin and of other organic biocides (3), experience in preparing polymers and in formulating and testing coatings (4), a program for the evaluation of certain polymer-bound antifouling polymers was started.

Our work has been aimed at:

1. Providing polymeric materials with long term antifouling action.
2. Developing safe, active substances by studying the mode of action and the toxicity of these compounds.

Special attention has been given to the influence of the chemical structure of the polymeric backbone on the rate of the release.

Part of this work will be presented in this paper.

2. SYNTHESIS AND PHYSICAL PROPERTIES OF POLYMERIC BIOCIDES

During our investigations a large number of polymeric biocides have been prepared. Two

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synthetic methods can be applied. First, the preparation of special types of organotin vinyl monomers and polymerizing these monomers or copolymerizing them with commercial vinyl monomers such as acrylates or maleic anhydride. Secondly, the modification of commercial polymers by reacting these polymers with suitable organotin compounds. For reasons of economy and convenience the second method was chosen. The polymeric backbone was a copolymerization product of vinylmethylether or styrene with maleic anhydride or a derivative thereof. The free or potential carboxylic acid group was used to bind the biocidal moiety. These starting resins were commercial products, except one. Styrene-maleic anhydride copolymers with a high molecular weight are not commercial available. This type of polymer has been prepared by reaction of equimolar ratios of the monomers in methylethyl ketone at 80° C with azo isobutyronitril as a catalyst. When the viscosity of the reaction mixture reached a value of ±1000 poises as measured on a sample at 20° C, the mixture was cooled down to room temperature and the polymer was precipitated under vigorous agitation by pouring it slowly into water. The molecular weight as determined by viscosimetry proved to be about 10^5.

The basic polymer types, the biocides and the reaction path to obtain the polymeric biocides is given in Figure 1 *a* and *b*. The preparation is simple. Equimolar amounts of the constituents, based on the acid number of the polymer, have been dissolved or suspended in an aromatic hydrocarbon (e.g. xylene) and refluxed for several hours. When R_3SnOH was used or when half-esters or amides were one of the reaction partners, the water formed was removed by azeotropic distillation. Table 1 records some physical data of the basic polymers and their reaction products.

In contrast to the parent polymers the resulting organotin polymers are soluble in aromatic hydrocarbons and/or ketones and yield transparent coatings. Their solubility depends primarily on the structure of the triorganotin constituent and secondarily on the molecular weight and structure of the basic polymer. As an example, solubility decreases in the sequence tri-n-butyl, tricyclohexyl-, triphenyltin. The triorganotin polymers can be applied to all kinds of substrates such as metals precoated with epoxy or vinyl resins, but also to glass, wood or concrete.

3. BIOCIDAL PROPERTIES

It is well known that the submerged surfaces in seawater in the first stage are colonized by a number of bacterial species (5). These bacteria form a slime exudate containing polysaccharides and protein polymers. The gelatinous bacterially secreted layer should provide a physical substrate for the settling of spores of algae and the larvae of barnacle species. There are doubts upon this hypothesis.

Therefore, we have attempted to include in our experiments the study of the bioactivity of our polymeric biocides on these marine bacteria. This has been done by investigating the slime formation on test panels exposed to seawater on a raft by means of visual observation or by manually touching the surface of the panels. However, these methods failed, due to the formation of a dirty layer of settled pelagic organic and inorganic matter on the test panels. Investigations based on microbiological techniques, such as the determination of the species and the accumulation of the number of the microorganisms with the aid of seawater-agar cultures in Petri discs could not be performed under the field test conditions.

The bioactivity of the polymeric biocides on algae and barnacles was investigated in the TNO Static Testing Station in the harbour of Den Helder. A large number of panels on racks in the raft have been exposed to seawater, in order to study the fouling with algae and barnacles. The above mentioned organotin polymers, dissolved in xylene or another appropriate solvent, were applied to Trovidur PVC panels. The surface was cleaned beforehand by wiping with xylene. The panels were attached to the racks in two ways: the first group 30 cm beneath the water surface in a horizontal position (on these panels only algae will grow); the second group of panels in a vertical position at about 1.5 m depth (on these panels larvae of barnacles will settle and grow preferentially).

The panels were checked at regular times. The fouling with algae or barnacles was expressed as the percentage of coverage of the

TABLE I

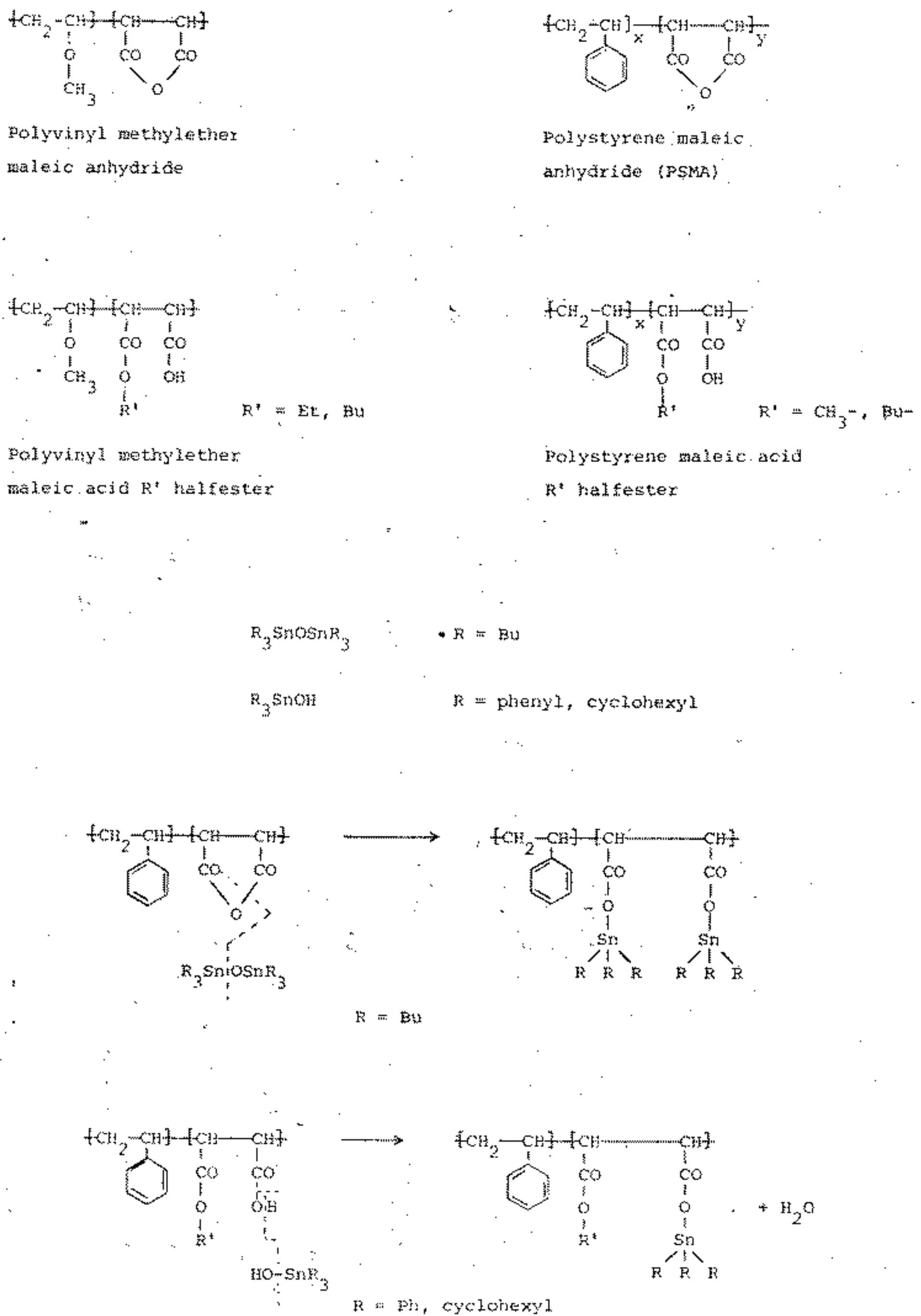
TRIORGANOTIN COPOLYMERS PREPARED FROM MALEIC ANHYDRIDE COPOLYMERS

Basic materials							End product		
Code	Resin					R_3Sn	Film properties	% R_3SnO	
	Trade name	Composition	Ratio	M.W.	A.N	R		Calc.	Found
1	Gantrez AN 149	VME-MA	1:1		715	Bu	Moderately hard	81.4	77.7
2	Gantrez ES 225	VME-MA (Et)	1:1		263	Bu	Hard	62.3	60.0
3	Gantrez ES 425	VME-MA (Bu)	1:1		230	Bu	Hard	58.9	57.9
5	Arco 1000 a	ST-MA	1:1	1.600	480	Bu	Visc.	74.7	70.3
6	Arco 2000 a	ST-MA	2.2:1	1.700	350	Bu		66.3	
7	Arco 3000 a	ST-MA	2.95:1	1.900	275	Bu		61.2	
8	TNO I	ST-MA	1:1		481	Bu	Moderately hard	71.5	
9	Suprapal AP 20	ST-Ma (R')			155	Bu	Moderately hard	46.2	
10	Lytron 822	ST-Ma (R')		10.000	241	Bu		57.8	
10 a	TNO II	ST-MA (Bu)	1:1 *		390	Bu	Moderately hard	69.7	
11	Gantrez AN 149	VME-MA	1:1		715	C_6H_5	Brittle	83.9	80.7
12	Gantrez ES 425	VME-MA (Bu)	1:1		230	C_6H_5	Brittle	63.2	60.7
13	Arco 1000 a	ST-MA	1:1	1.600	480	C_6H_5	Brittle	79.4	80.4
14	Gantrez AN 149	VME-MA	1:1		715	C_6H_{11}	Brittle	84.6	74.6
15	Gantrez ES 425	VME-MA (Bu)	1:1		230	C_6H_{11}	Brittle	64.3	61.7
16	Arco 1000 a	ST-MA	1:1	1.600	480	C_6H_{11}	Brittle	80.4	73.1

* ST/MA/MA (Bu) 1:0.7:0.3

Gantrez	GAF-Corporation
Arco	Atlantic Richfield Company
Suprapal	BASF
Lytron	Monsanto

VME = Vinyl methylether
ST = Styrene
MA = Maleic anhydride
MA (R') = Maleic acid half-ester
AN = Acid number



Polyvinyl methylether maleic anhydride

Polystyrene maleic anhydride (PSMA)

Polyvinyl methylether maleic acid R' halfester

R' = Et, Bu

Polystyrene maleic acid R' halfester

R' = CH_3-, Bu-

$R_3SnOSnR_3$ R = Bu

R_3SnOH R = phenyl, cyclohexyl

R = Bu

R = Ph, cyclohexyl

FIG. 1

surface. Table 2 presents the results of an exposition period of about one year.

As can be seen only polymer 8, which is a polystyrene-maleic acid tributyltin esther with a high molecular weight, fully prevents fouling by both algae and barnacles.

It is known that the antifouling activity of organotin compounds is higher against barnacles than against algae. In some cases (9, 10, 14 and 16) we found that the activity against algae was higher. The polymers 9 and 10 are half-esters (with lower Sn contents), while 14 and 16 contain tricyclohexyltin in the polymeric system. This phenomenon should be studied further.

The polymers with a triphenyltin moiety have not been tested in this series because their solutions turned out to be gelled after standing for some time. Moreover, coatings from triphenyltin polymers proved to be brittle and therefore less attractive as antifouling materials.

4. DYNAMIC TESTS

In addition to the static raft panel test, two different dynamic tests have been carried out on the coatings containing polymeric biocides:

1. Determination of the erosion rate of the coating.

TABLE 2

ANTIFOULING PROPERTIES OF TRIORGANOTIN POLYMERS

TRIORGANOTIN POLYMER				% OF FOULING			
				Algae		*Barnacles*	
No.	*Polymer*	*R_3Sn*	*R_3SnO (%)*	*7****	*12*	*7*	*10*
1	Gantrez AN 149	Bu	81.4	0	80	0	10
2	Gantrez ES 225	Bu	62.3	40	70	0	100
3	Gantrez ES 425	Bu	58.9	30	30	0	100
5	Arco 1000 *a*	Bu	74.7	10	80	0	70
6	Arco 2000 *a*	Bu	66.3	50	40	0	10
7	Arco 3000 *a*	Bu	61.2	0	50	0	70
8	PSMA * (TNO)	Bu	71.5	0	0	0	0
9	Suprapal AP 20	Bu	66.2	0	10	30	100
10	Lytron 822	Bu	57.8	10	10	10	100
10 *a*	PSMA * Butyl half-ester (TNO)	Bu	69.7			0	10
14	Gantrez AN 149	C_6H_{11} **	84.6	10	20	0	100
15	Gantrez ES 425	C_6H_{11} **	64.3	30	80	0	20
16	Arco 1000 *a*	C_6H_{11} **	80.4	30	0	40	100
17	No polymeric biocide		0.0	90	100	30	100

* Polystyrene maleic anhydride.
** Cyclohexyl.
*** Exposition in months.

2. Determination of the leaching rate of the toxic compounds.

Panels provided with shop primer and anticorrosive vinyl system have been coated with triorganotin polymers and after appropriate drying were rotated on the TNO rotor apparatus at a speed of 10 miles/hour for a period of 5 months, while the seawater was continuously refreshed.

After 0.5, 1, 2, 4 and 5 months the amount of erosion was measured by the decrease of the thickness of the coating with the aid of a Permascope with digital reading on every panel at 10 points. Six selected triorganotin polymers were thus investigated. Two coatings which were relatively soft failed immediately, because they did not withstand the turbulence of the seawater due to cold flow. For the other polymers, except one, the coating thickness could not be measured accurately over the whole period. All types of investigated

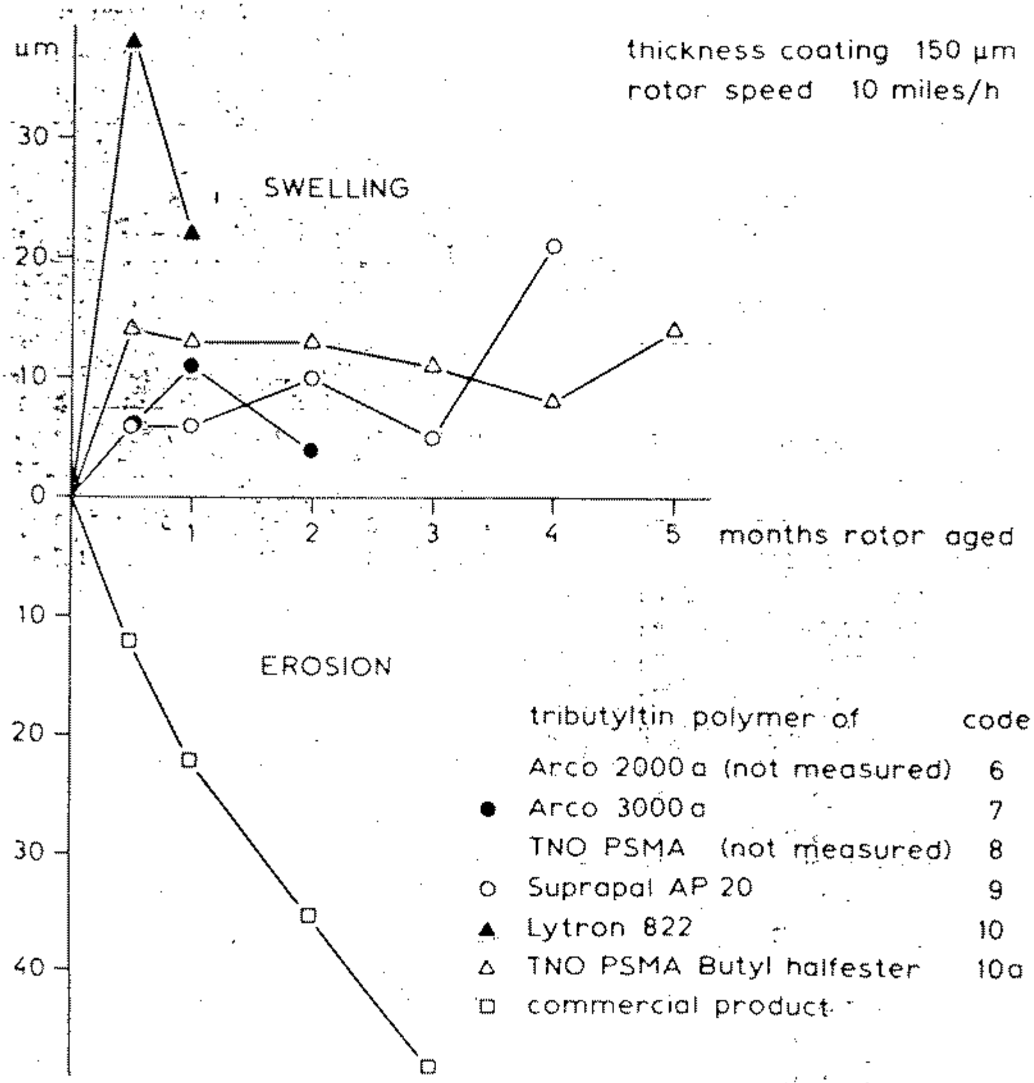


FIG. 2.—Erosion behaviour of tributyltin polymer coatings in seawater.

organotin polymers, except a commercial product based on a different polymeric backbone, showed a certain amount of swelling instead of erosion (Fig. 2). Erosion of the butyl half-ester is probable as can be seen on the graph.

Because panels coated with the tributyltin-butyl half-ester withstand the 5 month rotor test, these were subjected to the leaching test using a small laboratory rotor. After distinct ageing times on the rotor, panels were removed and attached to the laboratory rotor showed in Figure 3 and rotated during 25 hours in 800 ml of artificial seawater (3 %) at a pH of 7.97 and a temperature of 25° C (Fig. 4). The dissolved TBTO was analysed according to a new method developed in 1978 at TNO (6). An advantage of this method is, that the leaching rate of different tin moieties incorporated into polymeric systems can be determined.

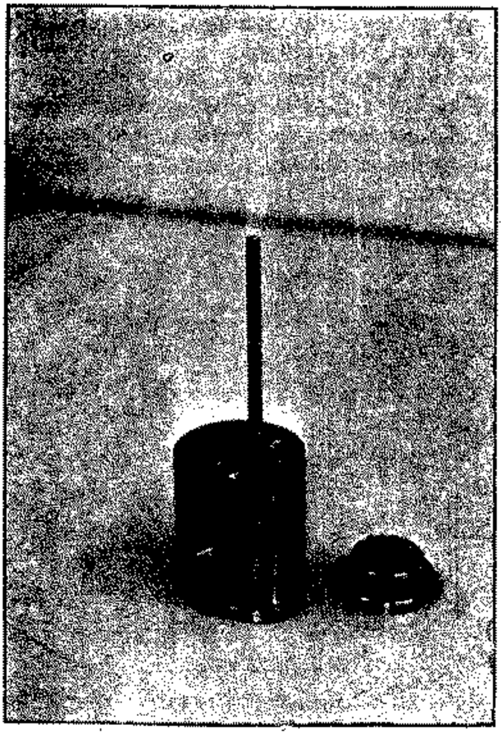


Fig. 3.—Laboratory rotor.

Table 3 gives the results of the leaching test of the tributyltin ester of polystyrene maleic acid butyl half-ester. It shows that already after half a month of rotation in seawater the release of TBTO reached a level too low to prevent fouling. As a consequence, these panels when immersed in seawater on the raft had been fouled completely within six weeks. This behaviour is not easily explained. It is plausible that the swelling of the coating was caused by water absorption due to the presence of free carboxylic acid groups throughout the whole layer. On the other hand Ca^{++} and Mg^{++} cations can form a barrier on the surface of the coating by ion binding with the free carboxylic acid groups retarding the dissolution of free TBTO or tributyltin chloride into the surrounding seawater. Results of investigations described in the next part of this paper support this hypothesis.

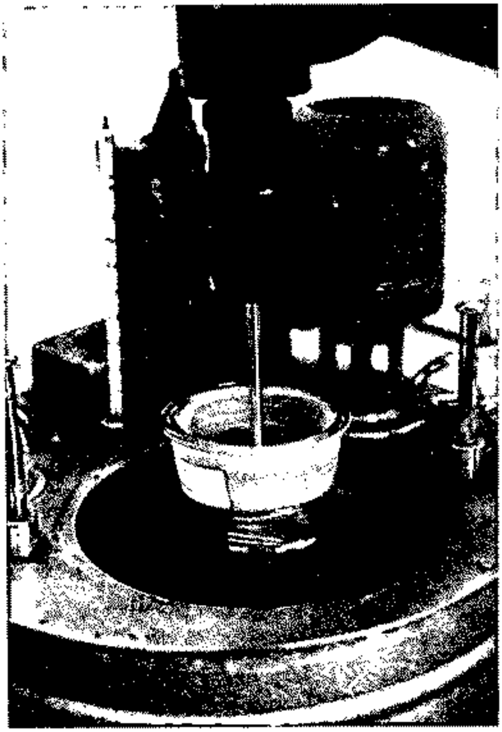


Fig. 4.—Laboratory leaching apparatus.

5. ORGANIC BIOCIDES BOUND TO POLYMERS

Part of our research has been the development of slow-release antifouling polymers based on organic biocides covalently bonded to a polymeric backbone.

There were several reasons to start with a study of this type of polymeric biocides:

1. The patent literature contains data about antifouling paint formulations with dissolved or dispersed organic biocides.

2. Whereas the application of organic compounds as fungicides, insecticides and herbicides has been studied quite extensively, there has been given little attention in the literature to the relation of these biocides with antifouling activity.

3. These investigations may widen the scope of antifouling polymers by incorporating an organic compound into organotin polymers as a co-biocide, giving a completely new type of materials. Beneficial effects such as synergism may play a role in the mode of action of these mixed polymeric biocides.

4. Organotin carboxylates in contact with seawater are subject to hydrolysis. This reaction, however, is in fact too fast. Covalently bonded organic compounds, e.g. through an ester or amide bond will hydrolyse slowly, perhaps too slowly to build up a satisfactory biocidal concentration of the boundary of the coating surface. It was found (7) that specific groups such as carboxylic acid groups attached to a polymer chain may increase the rate of hydrolysis of the ester and amide bonds. Because seawater is a very complex medium with a relatively high concentration of mono and divalent cations (Na^+, Ca^{++}, Mg^{++}) it is of great importance to investigate this effect

TABLE 3

AMOUNT OF TBTO LEACHED IN 24 h AFTER ROTOR AGEING

(tributyltin ester of polystyrene maleic acid butyl half-ester)

Ageing time of panel (months)	*μg TBTO/cm²/day*
0	4.17
0.5	0.44
1	0.36
2	0.55
4	0.53
5	1.89

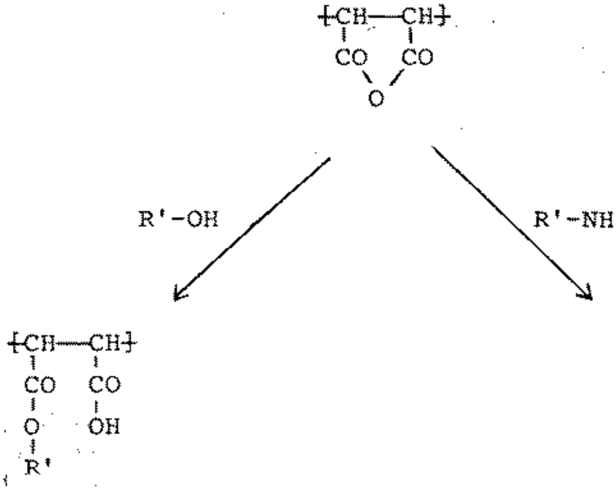


FIG. 5

TABLE 4

BIOCIDAL ACTIVITY OF SOME ORGANIC AND ORGANOMETAL COMPOUNDS AGAINST THE LARVAE OF ARTEMIA SALINA L.

Compound	*LD 90/24 h at ppm*
Di-n-octylamine	0.1-1
Dodecylamine	1
p-Amino azo benzene (AAB)	1
Pentachlorophenol	10-100
8-Hydroxyquinoline	100-1000
Tributyltin oxide	0.1
Tributyllead acetate	<1
Tributylgermanium acetate	<1
Phenylmercury acetate	1
Dibutyltin oxide	>1000

on the rate of hydrolysis under these extreme conditions.

Polystyrene maleic anhydride was chosen as the polymeric backbone, because the anhydride group is very reactive towards hydroxyl or amino groups resulting in the formation of an ester of amide bonding adjacent to a free carboxylic acid group (Fig. 5).

A screening program of potentially organic antifoulant compounds was started with the nauplius larvae of *Artemia salina* as the test organism. The larvae can be easily cultivated from the eggs, which are sold as brine shrimp eggs. This test has been described in the literature as an insecticide assay (8).

Preliminary experiments showed that bis(tributyltin) oxide has a fast lethal effect on the larvae still at the 0.1 ppm level. The same was found to be true for tributyllead acetate and phenylmercury acetate, which are known antifouling agents. The concentration of the potential larvaecide resulting in a death rate of 90 % of the larvae (hatched from 10 mg of eggs in 10 ml of artificial seawater) in 24 h at room temperature (LD 90) was used as an indication for antifouling activity.

Numerous organic compounds have been tested. However, only a few compounds proved to be active. A list of selected active compounds, suitable for attaching to polystyrene maleic anhydride, together with some reference materials, is given in Table 4.

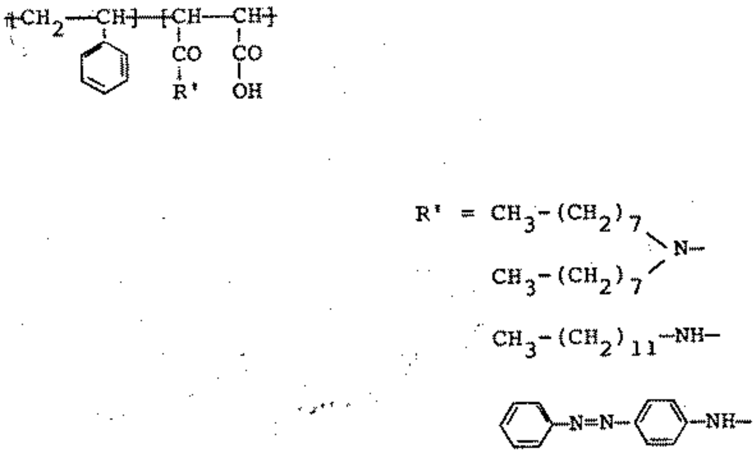


FIG. 6

Polymeric biocides were prepared with the compounds: di-n-octylamine, dodecylamine and p-aminoazobenzene. The molecular structures are given in Figure 6.

All materials were very brittle and showed bad film-forming properties. In order to investigate their antifouling activity with the aid of the raft test on panels in the open sea these compounds had to be mixed thoroughly with a binder (a common method to investigate powdery materials such as cuprous oxide).

Incorporation of triorganotin compounds such as bis(tributyltin) oxide into polymeric biocides by reacting these compounds with the free carboxylic acid group of the polymer afforded new types of antifouling polymers (Figure 7). The introduction of the triorganotin moiety improved the film-forming and solubility properties of the polymer.

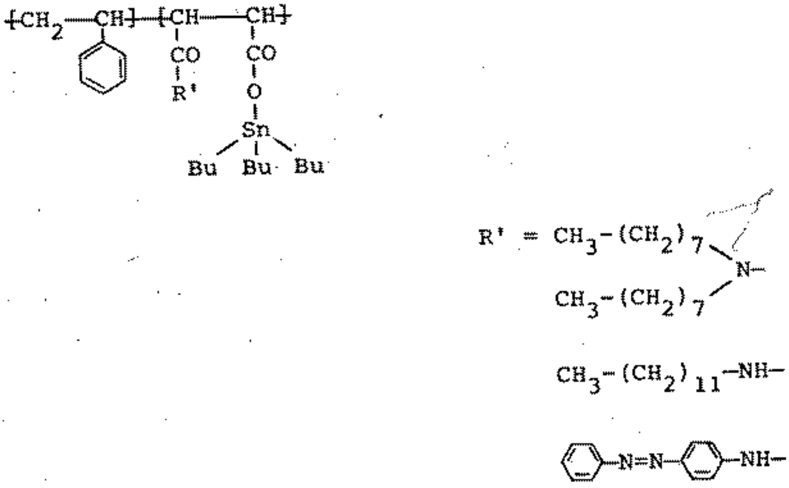


FIG. 7

Table 5 contains preliminary fouling data with test panels for algae and barnacles up to 42 weeks exposition. The polymers containing organic biocides failed completely. However, when both an organic and an organotin compound had been attached to a PSMA polymeric backbone a good antifouling activity was observed. Other experiments have to be done to collect more pertinent data.

Because of the strong fouling with barnacles of the test panels coated with the polymeric systems containing only organic biocides, some investigations were carried out to trace the cause of this failure. One reason could be a too low rate of hydrolysis resulting in a sublethal concentration of biocide on the coating surface.

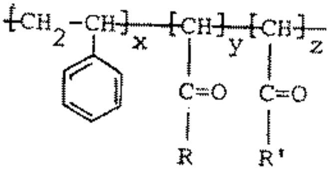
The PSMA-p-aminoazobenzene system was chosen as a model in laboratory leaching experiments. Hydrolysis of the amide bonds of this insoluble polymer gives free p-aminoazobenzene (AAB) resulting in the formation of a yellow solution. The concentration of AAB can simply be measured with the aid of a colorimeter or spectrophotometer recording the absorbance of a wavelength of 375 nm. A series of suspensions was made of 0.1 wt % of the ground polymer in 3 % seawater at different pH values in glass vessels. After gentle shaking for 8 days at 24° C the amount of AAB formed was measured in the filtrate and the polymer residues were suspended again in fresh seawater. This procedure was repeated and continued for 20 weeks. In one experiment seawater was substituted by a 3 % NaCl solution (pH 7). The leaching curves of this series of experiments are recorded in Figure 8.

From these curves the following conclusions can be drawn:

1. This copolymer is susceptible to hydrolysis.

TABLE 5

ANTIFOULING PROPERTIES OF MIXED BIOCIDE COPOLYMERS (% OF FOULING)



$x = 1$

y is given in the table

$z = 1 - y$

$R' = -OH,\ -O-SnBu_3$

PSMA derivative		R' = —OH						R' = O—SnBu₃					
R	Molar ratio y	Algae			Barnacles			Algae			Barnacles		
		3 *	8	42	3	8	42	3	11	42	3	11	42
Dioctylamine	0.45		40	100		60	100	10	0	0	0	0	100
Dodecylamine	0.38		30	20		30	100	0	0		0	0	0
Amino azo benzene (AAB)	0.34		10	10		80	100	10	30	20	0	0	
Butanol	0.30	100			100				10			30	10
Triphenyltin oxide	0.25							10	40	10	0	0	100
Control		100			80	80	100	100			80		100
Commercial product **								0	60	30	0	10	20

* Exposition in weeks.

** Acrylate resin without an organic biocide.

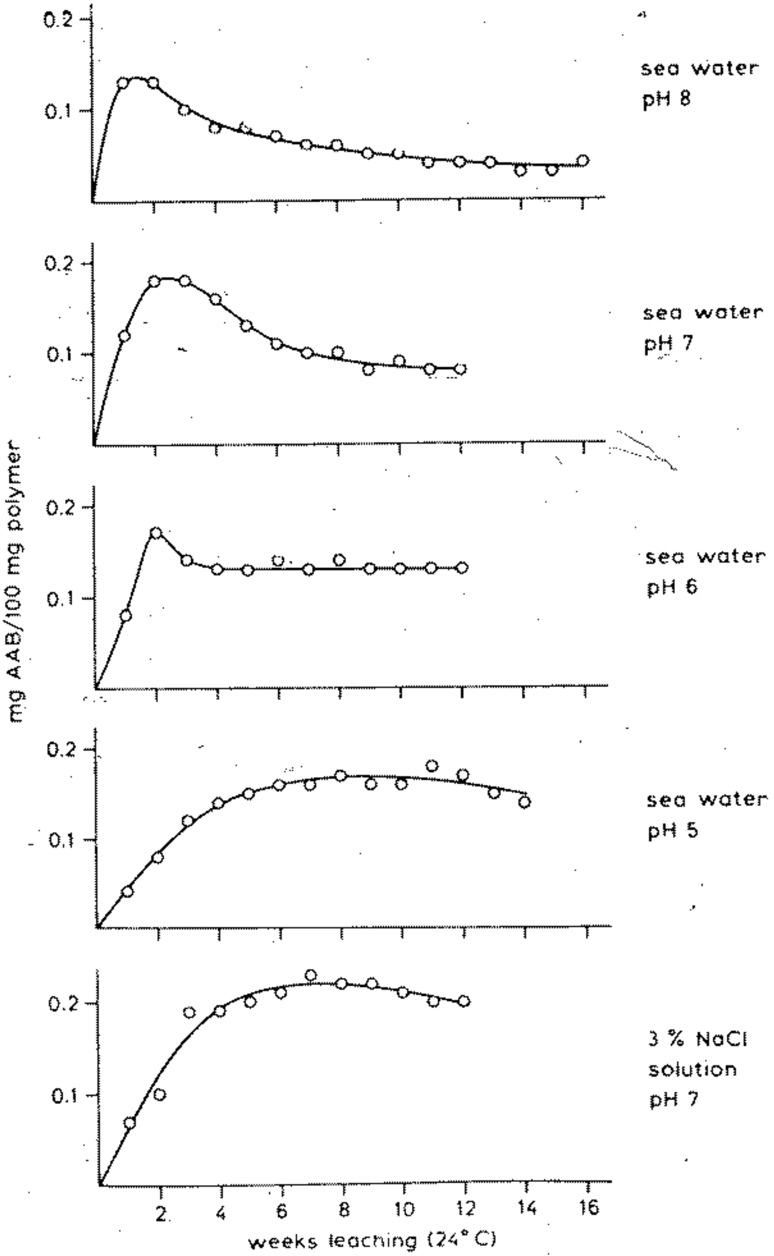


FIG. 8.—Leaching of PSMA-AAB polymer in seawater and in 3 % NaCl solution at different pH values.

2. The rate of hydrolysis is small and the amount of released p-aminoazobenzene is low (<0.2 mg/100 mg of polymer/week).

3. The release pattern is strongly influenced by the pH of the seawater.

4. There is a difference in the release patterns of the polymer in seawater and in a 3 % sodium chloride solution at pH 7.

The poor results of the test panels discussed above are in accordance with the low rate of hydrolysis. The release of AAB from these panels, which can be calculated from the leaching experiments, proved to be initially smaller than 2 μg/cm²/day [TBTO is active at a leaching rate of 1.5 μg/cm²/day (9)]. Moreover, at pH 8 which is the normal pH of open sea water, the rate of release decreased within a few weeks from 0.11 mg to 0.02 mg/100 mg/week. Calculations on the basis of extrapolation indicate that the leaching from test panels decreases to about 0.1-0.2 μg/cm²/day. This phenomenon is in contrast with the curves at pH 6 and 5, which show a constant release. From these results and from the difference of the release patterns in seawater and in 3 % NaCl solution at pH 7 it is postulated that:

1. At pH 7 and 8 the polymeric material containing free carboxylic acid groups has been covered by a precipitate consisting of an insoluble calcium and/or magnesium maleate formed by reaction of calcium and/or magnesium divalent cations with the carboxylic acids groups of the hydrolysed anhydride. At pH 5 and 6 and in a 3 % NaCl solution at pH 7 this insoluble salt cannot be formed.

2. This salt layer decreases either the penetration of water into the polymer or the leaching rate of hydrolysed PAA.

These results support the above mentioned hypothesis that the decreased leaching rate of TBTO from the tributyltin carboxylate of polystyrene maleic acid butyl half-ester (Table 3) measured with the laboratory equipment is due to the formation of a salt barrier.

These experiments demonstrate that with this type of polymeric backbones the pH has a strong influence on the leaching rate and that the substitution of seawater by a 3 % sodium chloride solution for reasons of convenience may lead to false conclusions.

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ESTUDIOS ECOLOGICOS PRELIMINARES SOBRE LAS COMUNIDADES INCRUSTANTES DE PUERTO QUEQUEN (ARGENTINA) *

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RESUMEN

El presente trabajo tiene por principal finalidad dar a conocer los resultados preliminares de las investigaciones sobre comunidades incrustantes de Puerto Quequén, con referencia a su acción perjudicial en los sistemas de refrigeración de la central termoeléctrica ubicada en la zona.

Dado que no existían antecedentes de trabajos previos sobre el tema, fue necesario realizar observaciones hidrológicas generales y estudios básicos sobre la fauna bentónica local.

Para la obtención de organismos incrustantes, determinación de sus ciclos de fijación y análisis de las variaciones de biomasa se emplearon paneles experimentales ubicados en tres niveles de profundidad diferentes (desde superficie hasta aproximadamente 2 m); el ensayo fue realizado durante el período septiembre 1977/agosto 1978.

Los sustratos experimentales se ubicaron en dos zonas: externa, correspondiente a la toma de agua de la central, e interna, correspondiente a la primera sección del sistema de refrigeración. Cada una de estas zonas se estudió en forma independiente con sistemas de paneles mensuales y acumulativos, lo que permitió comparar los ciclos de fijación de los organismos y las fluctuaciones de la biomasa en ambas zonas, ya que en las mismas predominan diferentes condiciones ambientales.

El presente estudio sirve de base para la aplicación de sistemas de control en los circuitos de refrigeración de la central, así como también para futuros ensayos de pinturas antiincrustantes.

1. INTRODUCCION

Las investigaciones sobre comunidades incrustantes de las costas argentinas habían sido enfocadas hasta el presente exclusivamente hacia los problemas que las mismas ocasionan en embarcaciones y construcciones portuarias, no existiendo antecedentes sobre estudios en sistemas de refrigeración.

Este aspecto fue encarado recientemente a raíz de un pedido efectuado por la Dirección de la Energía de la Provincia de Buenos Aires (DEBA), motivado por los serios problemas ocasionados por las incrustaciones en los sistemas de refrigeración de la central termoeléctrica de Puerto Quequén.

En base a este pedido, y teniendo en cuenta la carencia de estudios previos sobre las comunidades bentónicas locales, se planeó desarrollar un estudio general a lo largo de un ciclo anual (septiembre 1977/agosto 1978), utilizando sustratos experimentales, a los efectos de obtener un panorama preliminar del problema y sus posibles soluciones. Cabe señalar que en años anteriores uno de los autores ha-

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* Trabajo realizado por convenio entre el INIDEP y el LEMIT.

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*** DEBA, Dirección de la Energía de la Provincia de Buenos Aires, La Plata, Argentina.

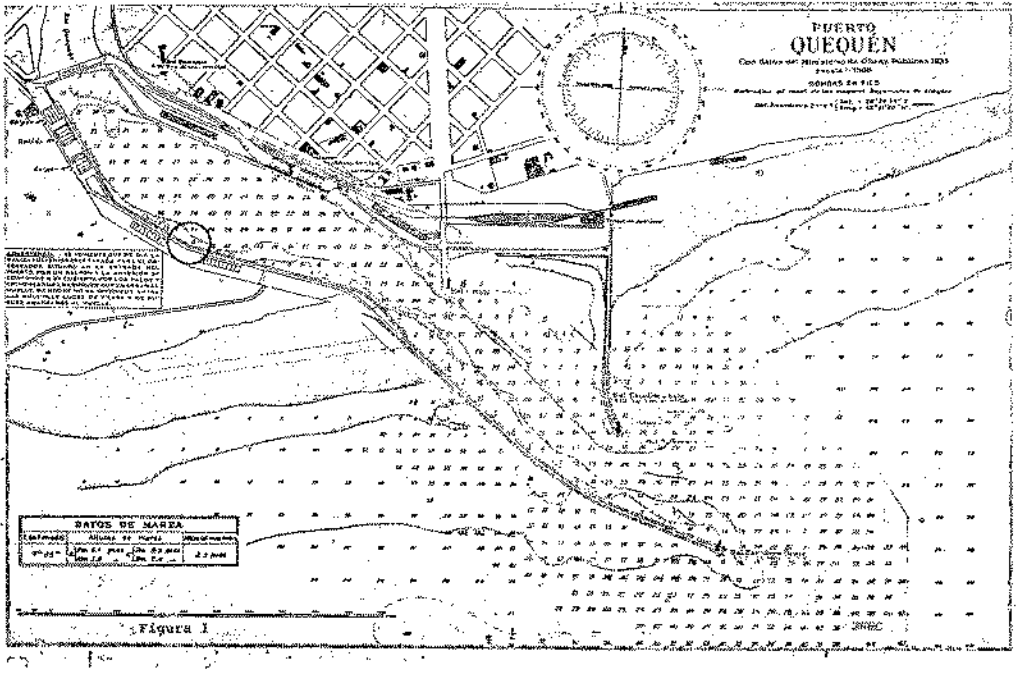

Fig. 1

bía efectuado una inspección en los sistemas de refrigeración de la central con la finalidad de conocer los alcances de dicho problema (3).

En esta primera etapa, los estudios se han limitado al análisis de los ciclos de fijación de los organismos y de las variaciones en la biomasa de la comunidad, dejándose para una etapa posterior el estudio de la evolución de la misma.

Estos estudios serán complementados en el futuro con otros que se están llevando a cabo en la zona y que se espera sean de utilidad para la aplicación de sistemas de control en la central, así como también para ensayos de pinturas antiincrustantes en embarcaciones locales.

2. AREA DE ESTUDIOS

Se trata de una zona con características peculiares desde el punto de vista hidrológico, debido a la influencia recíproca que se establece entre la masa de agua de origen marino y los aportes fluviales. Como consecuencia, a lo largo del día y de las estaciones del año se producen marcadas variaciones de los factores ambientales, principalmente en lo que respecta a la salinidad y temperatura de las aguas, que pueden repercutir de diversas formas en las comunidades incrustances.

El río Quequén Grande nace en la laguna Quequén y su desembocadura al océano Atlántico se produce a los 38° 36' S y 58° 40' O, recibiendo afluentes de caudal variable a lo largo del año. Presenta un ancho máximo de, aproximadamente, 60 m y su profundidad natural es de 1,8 m como mínimo, si bien en épocas de crecientes producidas por las lluvias su nivel puede aumentar a 3 m. El caudal de agua del río suele ser considerable, aun en las épocas de mayor sequía.

En la zona próxima a la desembocadura del río Quequén Grande se encuentra emplazado el Puerto Quequén (fig. 1), en cuyo ámbito está situada la central termoeléctrica de DEBA. Este puerto está limitado en su desembocadura por dos escolleras: la del oeste, que es la principal, corre de NO a SE, con una longitud de 1.192 m, y la del este, de 572 m de largo, corre de N a S, existiendo entre ambas un paso de 200 m. Presenta una zona de dragado de ancho variable, que oscila entre 7,3 m y

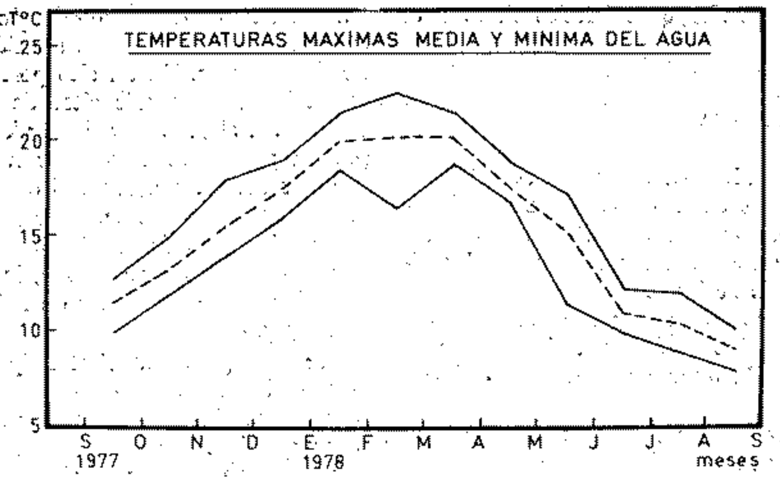

FIG. 2

6,4 m como mínimo de profundidad, admitiendo un calado máximo de 8,23 m con altas mareas y con mar calmo.

En cuanto al régimen de mareas, el establecimiento del puerto medio de Quequén es de 5 horas 45 minutos; la amplitud de la marea de sicigias medias es de 1,3 m, y la de cuadraturas medias, de 0,9 m. Estas mareas producen corrientes que se hacen sentir hasta algunas millas de la costa con una intensidad de 0,5 a 1 nudo, aunque en casos excepcionales pueden ser mayores; en la zona de la desembocadura, las corrientes de marea llegan a ser más intensas, hasta de 2 nudos en el último período de vaciante. Este factor hace que se establezcan influencias recíprocas entre las masas de agua marina y fluvial, registrándose el efecto de la marea hasta 3 km dentro de la zona del río.

También debe tenerse en cuenta la influencia de la dirección e intensidad de los vientos sobre la amplitud de marea y la magnitud de la corriente de marea.

Los ensayos del presente trabajo fueron realizados en la toma de agua y sala de bombas de la central de DEBA, cuya ubicación se indica con un círculo en la figura 1.

A continuación se comentan los principales

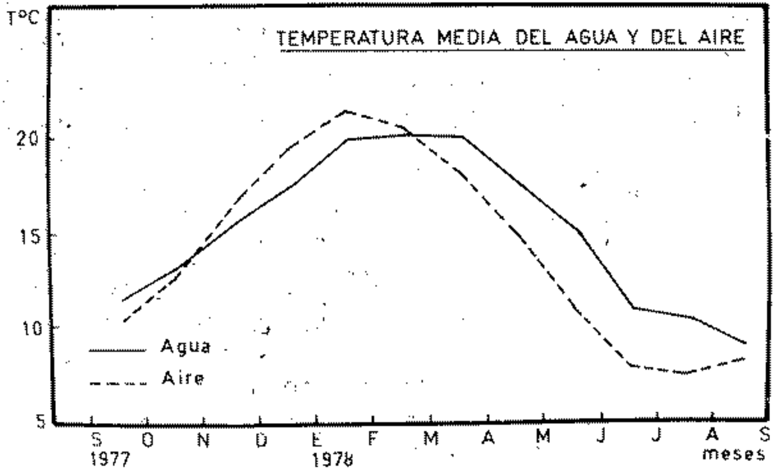

FIG. 3

factores ambientales considerados durante el estudio.

2.1. TEMPERATURA

De acuerdo a los estudios realizados en otras áreas portuarias del país, se ha podido determinar que la temperatura del agua constituye uno de los principales reguladores de los ciclos de fijación de los organismos incrustantes y del desarrollo de las comunidades que ellos integran, de ahí la importancia de conocer en forma precisa la dinámica térmica a lo largo del año.

La temperatura media del agua superficial, a la altura de la toma de la central de DEBA, ha presentado una variación anual de aproximadamente 11° C; la amplitud térmica máxima para un mismo mes fue de 6° C y se registró en el mes de febrero. Durante este mes se registró también el valor máximo de temperatura de 22,5° C, mientras que el mínimo, de 8,0° C, tuvo lugar en el mes de agosto (figura 2).

La curva de la temperatura media del aire resulta semejante a la del agua, notándose claramente la influencia que existe entre ambos factores (fig. 3).

El patrón térmico que presenta Puerto Quequén es muy similar al observado en el puerto de Mar del Plata y Puerto Belgrano a lo largo de varios años (1, 2, 3, 5, 6, 9).

2.2. SALINIDAD

Como ya fue mencionado, el área de estudios se encuentra regulada por la influencia recíproca de las aguas marinas y fluviales. Consecuentemente, la salinidad del agua resulta ser un factor marcadamente variable, que podría condicionar importantes modificaciones en el desarrollo de los organismos incrustantes o afectar algunas de sus funciones básicas.

Las variaciones que se producen en la salinidad son de dos tipos: por una parte, existen fluctuaciones a lo largo del día, debido a la influencia de la marea. Para detectar estos cambios se obtuvieron muestras de agua superficial a distintas horas, registrándose en cada caso el estado de la marea. Puede observarse en la figura 4 la relación directa que existe entre los valores de salinidad y el estado de la marea. En un alto porcentaje de los casos, los valores más altos de salinidad corresponden al momento de la pleamar, en que pueden alcanzarse valores de hasta 33,0 por 1.000, semejantes a los típicos para el agua de mar de la zona. Durante la bajamar, la salinidad desciende notablemente, debido al aporte fluvial. De esta forma, la amplitud de salinidad diaria puede ser de más del 15 por 1.000 (fig. 4).

Por otra parte, en ciertas épocas del año, el caudal del río aumenta por efectos de las lluvias y se observan valores de salinidad más bajos que lo habitual, pero siempre se mantienen las variaciones diarias entre la baja y la pleamar. Una excepción a esto se produjo bajo ciertas condiciones especiales durante el mes de septiembre, en que la salinidad registrada fue muy baja y no se observó el efecto de la influencia marina durante la pleamar. Este fenómeno coincidió con un período de precipitaciones pluviales de gran magnitud, que ocasionaron inundaciones en toda la provincia de Buenos Aires. Los valores de salinidad volvieron al régimen normal en forma paulatina, al reducirse el caudal del río.

Durante el segundo semestre de 1978, la salinidad osciló entre 33 y 2,5 por 1.000. Dichos valores evidencian de por sí la importancia de este factor, ya que fenómenos como los anteriormente citados pueden producir valores muy bajos de salinidad, que resulten letales incluso para especies eurihalinas, como las que habitan en la zona. Los descensos bruscos de salinidad, por otra parte, pueden ocasionar el ingreso transitorio de organismos dulceacuícolas durante ciertos períodos.

Como complemento de los datos de salinidad correspondientes a este ensayo se incluyen otros obtenidos posteriormente al mismo (figura 5); a través de ellos pueden observarse las mismas fluctuaciones por influencia de la marea y valores muy bajos, coincidentes con crecidas del río, por efecto de lluvias. En la figura 6 se resumen los valores de salinidad máximos, mínimos y medios a lo largo de un período anual.

Este panorama con respecto a la salinidad presenta algunas similitudes con observaciones realizadas en la zona de Bahía Blanca, pero

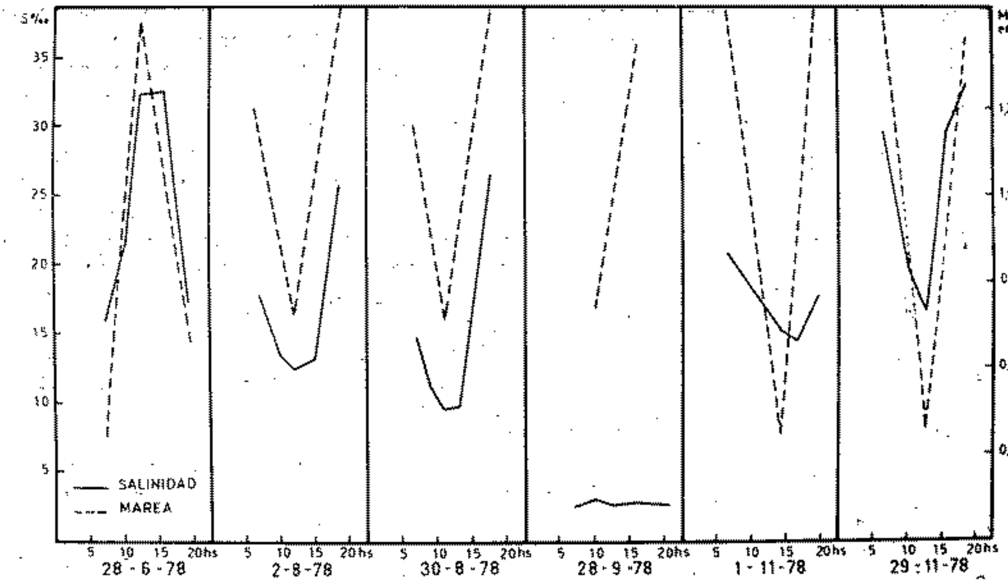

FIG. 4.—Relación entre la salinidad y el estado de la marea, período junio/noviembre 1978.

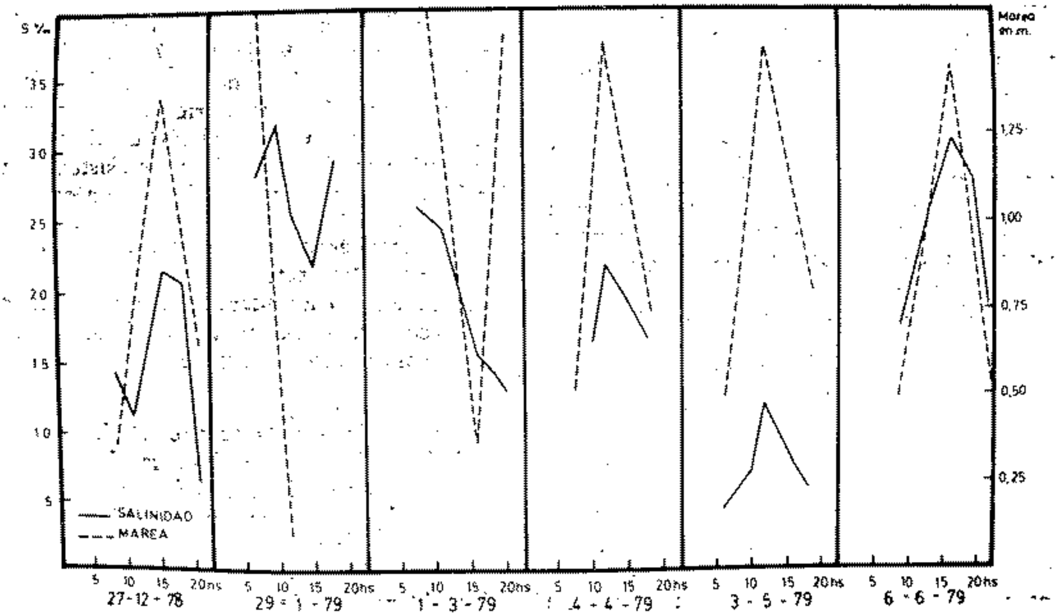

FIG. 5.—Relación entre la salinidad y el estado de la marea, período diciembre 1978/junio 1979.

difiere notablemente del esquema que presenta el puerto de Mar del Plata, en donde los valores de salinidad son muy estables a lo largo del año y éste no constituye un factor que influya marcadamente en la dinámica de las comunidades incrustantes locales (1, 2, 3, 9).

2.3. pH

Este factor interesa principalmente en relación a los fenómenos de contaminación. En aquellas zonas portuarias con gran aporte de materia orgánica y poca renovación de las aguas, el pH suele descender notablemente, como ha sido observado en el puerto de Mar del Plata (1, 2, 3, 9).

En la zona de Puerto Quequén, los valores de pH se han mantenido por encima de 8 a lo largo de todo el año, indicando la ausencia de procesos importantes de contaminación por materia orgánica. Los valores registrados, por otra parte, son compatibles con valores normales de oxígeno disuelto (fig. 7).

Con respecto a la transparencia del agua, no se observan notables diferencias a lo largo del año, y puede decirse que, en términos generales, las aguas del puerto Quequén presentan una mayor turbidez que las de la zona marina aledaña, debido a la presencia de sedimentos en suspensión. Los mismos son tanto de origen local como fluvial y aumentan notablemente durante los períodos de crecida por lluvias.

En cuanto a la turbulencia, la zona presenta una moda calma y siempre una turbulencia menor que la zona marina adyacente, si bien durante períodos breves ésta puede aumentar, debido a los efectos de vientos locales.

3. METODOLOGIA

Para la obtención de las muestras biológicas, estudio de los ciclos de fijación de los organismos incrustantes y análisis de la evolución de la comunidad se emplearon sustratos artificiales inertes, consistentes en paneles de acrílico arenado. Estos paneles fueron dispuestos en juegos y ubicados en tres niveles de profundidad diferentes, con la finalidad de obtener un muestreo representativo.

Cada juego estaba compuesto por dos paneles de acrílico superpuestos, de 30 × 10 cm y 2 mm de espesor, sujetos a un marco también de acrílico (fig. 8). Los tres juegos de paneles que componían cada sistema fueron suspendidos mediante una soga de nailon, sujeta por su extremo superior a un gancho amurado y en cuyo extremo inferior se colocó un peso para otorgar rigidez al conjunto (figura 8).

De acuerdo a la metodología de muestreo empleada, los paneles se dividieron en dos categorías:

a) Paneles mensuales, que son aquellos que permanecen sumergidos por períodos de treinta días y permiten bosquejar los ciclos de fijación de las diferentes especies.

b) Paneles acumulativos, que son aquellos que permanecen sumergidos por períodos progresivamente más largos, desde el primer mes de inmersión hasta el final del período establecido, y brindan información sobre la evolución de la comunidad incrustante.

La elección de las zonas de ubicación de los sistemas suscitó algunos inconvenientes, dada la imposibilidad de su colocación dentro de los canales de refrigeración, los que trabajan continuamente a caudal completo. Por este motivo se decidió ubicar los sistemas en dos lugares accesibles en todo momento:

a) Toma de agua (entrada al circuito) = = sistema externo.

b) Pileta decantadora de arena (sala de bombas, anterior a los filtros rotativos) = sistema interno.

Cada uno de estos lugares se estudió en forma independiente, con sistemas de paneles mensuales y acumulativos propios, a los efectos de poder comparar los ciclos de fijación de los organismos y la evolución de la comunidad incrustante en ambas zonas.

La obtención de muestras se llevó a cabo durante el período septiembre 1977/agosto 1978.

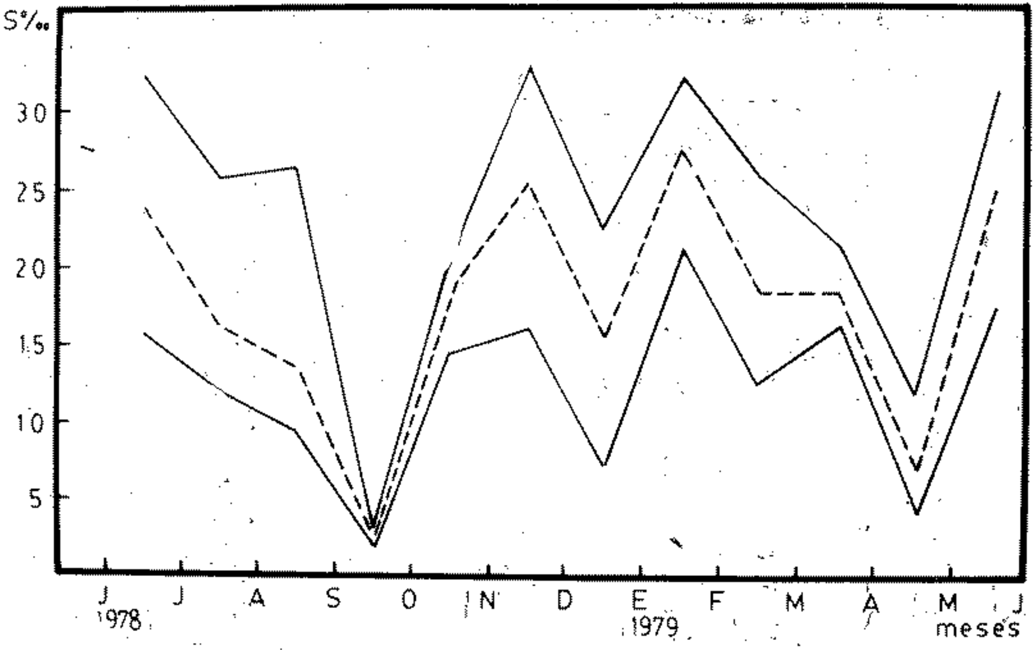

Fig. 6.—Salinidad máxima, mínima y media.

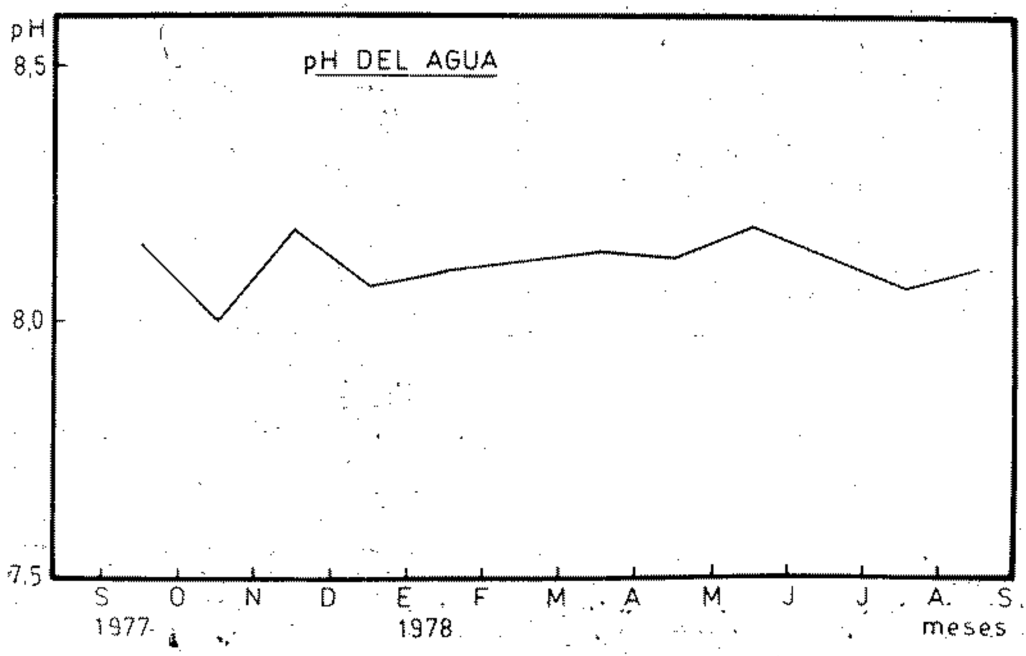

Fig. 7

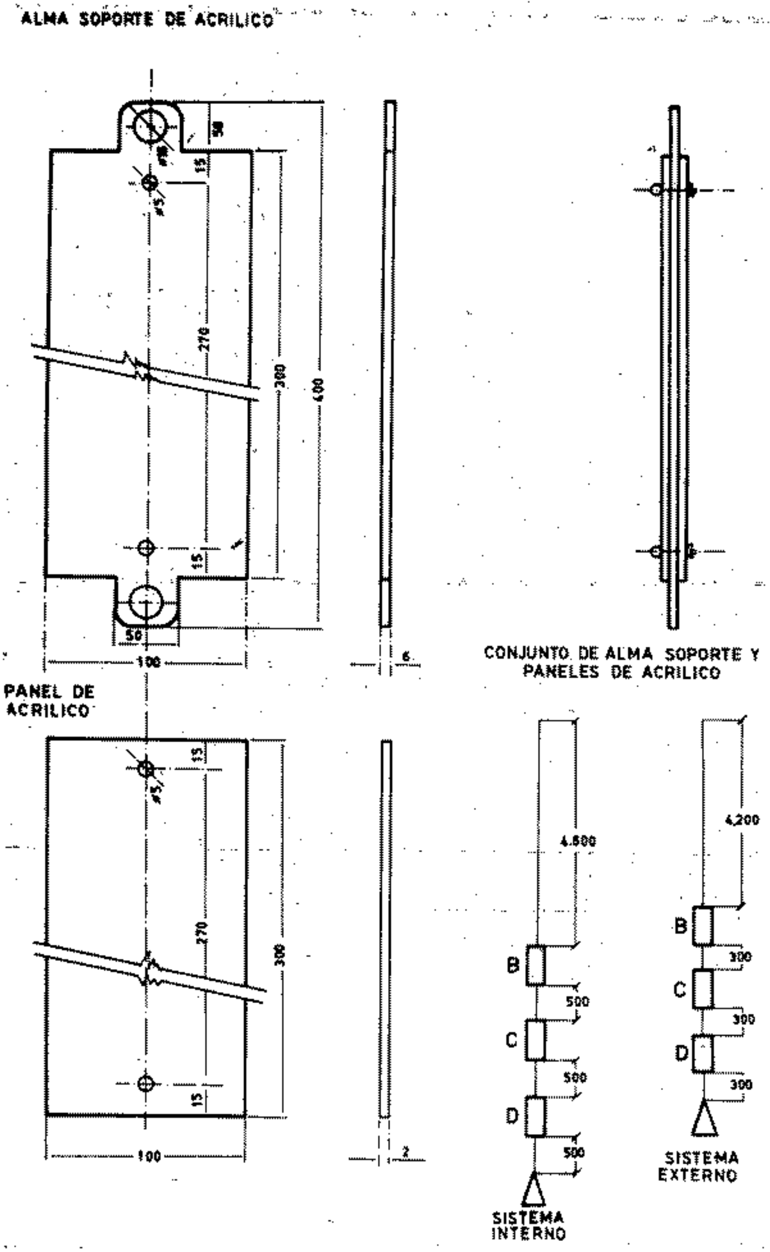

FIG. 8.—Esquema de los sistemas colectores.

Los muestreos se realizaron mensualmente, retirando el sistema mensual y el acumulativo correspondiente a ese mes. Una vez extraídos, los paneles fueron colocados en bolsas de polietileno con formol al 5 % para su posterior traslado. Los paneles mensuales eran reemplazados inmediatamente por nuevos juegos; los acumulativos se renovaban al final de cada cuatrimestre. De los dos paneles que componen el juego, uno se utilizó para el reco-

TABLA I

LISTA DE LOS ORGANISMOS REGISTRADOS SOBRE PANELES MENSUALES EN LA ZONA DE PUERTO QUEQUEN

ALGAS

Crisofitas

Achnanthes cf. *longipes*
Amphora sp.
Cocconeis sp.
Coscinodiscus spp.
Cyclotella sp.
Grammatophora cf. *marina*
Gyrosigma sp.
Licmophora cf. *abbreviata*
Melosira granulata
Melosira sulcata
Melosira sp.
Navicula cf. *grevillei*
Navicula spp.
Pinnularia sp.
Pleurosigma spp.
Rhoicosphenia sp.
Surirella spp.
Synedra spp.

Cianofitas

Callothrix sp.
Filamentosas indet.

Clorofitas

Enteromorpha spp.
Ulothrix sp.

Rodofitas indet.

ANELIDOS

Mercierella enigmatica
Polydora sp.
Errantia indet.

BRIOZOOS

Conopeum sp.
Cryptosula pallasiana

MOLUSCOS

Brachydontes rodriguezi
Mytilus platensis
Tenellia pallida

CRUSTACEOS

Copépodos

Harpacticoidea
Cyclopoidea

PROTOZOOS

Dinoflagelados

Exuviaella sp.
Peridinium sp.

Ciliados

Enchelydae cf. *Lacrymaria* sp.

Folliculinidae
Libres indet.
Vorticella sp.
Zoothamnium sp.

Suctorios

Acineta sp.
Ephelota sp.

Rizópodos

Amoeba sp.
Bolivina sp.

CELENTERADOS (= CNIDARIOS)

Hidrozoos

Campanulariidae
Tubularia sp.

Antozoos

Sagartentus bandae

ROTIFEROS

Colurella sp.
Trichocerca sp.

Isópodos

Gnathiidae
Sphaeroma sp.

Anfípodos

Corophium sp.

Cirripedios

Balanus amphitrite

Decápodos

Cyrtograpsus angulatus
Cyrtograpsus altimanus

TUNICADOS

Botryllus schlosseri

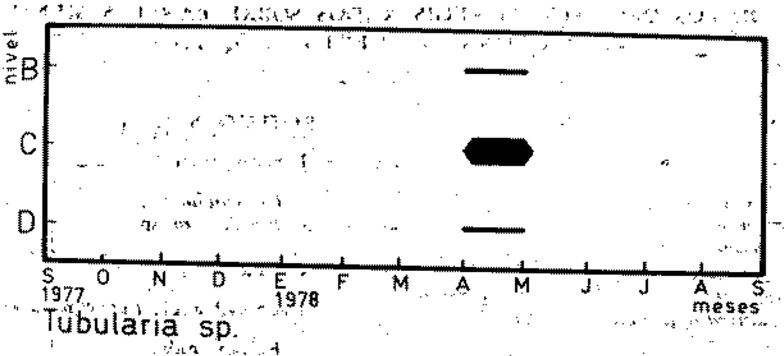

FIG. 9 *a*.—Ciclo de fijación, sistema externo.

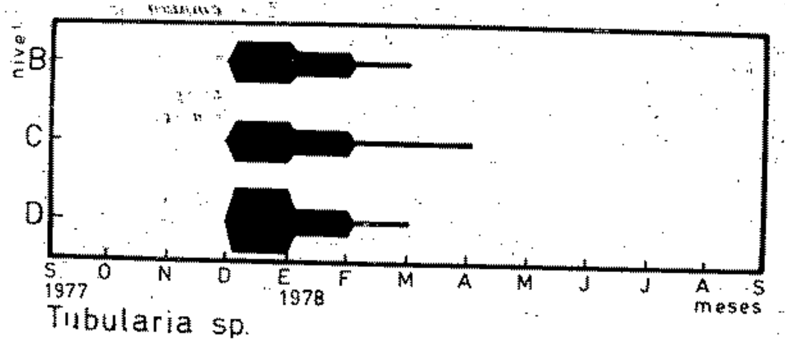

FIG. 9 *b*.—Ciclo de fijación, sistema interno.

nocimiento sistemático de los organismos, distribución espacial, etc., y el otro, para la evaluación de la biomasa.

Los paneles destinados al estudio de la biomasa fueron raspados sin efectuarse una observación previa y el material obtenido fue procesado para la determinación de peso húmedo, peso seco y peso cenizas, siguiendo las técnicas clásicas.

4. CICLOS DE FIJACION DE LOS PRINCIPALES ORGANISMOS INCRUSTANTES

De las especies registradas en los paneles mensuales (tabla I) se seleccionaron aquellas más significativas para graficar su ciclo de fijación. Como ya fue mencionado, se ha considerado por separado la colonización que se produce en los sistemas interno y externo, teniendo en cuenta las condiciones ecológicas diferentes que predominan en cada zona.

Los gráficos de fijación de los diferentes organismos fueron realizados en base a una escala de abundancia relativa que incluye cuatro categorías (abundante, frecuente, escasa y rara) y que se indican con trazos de distinto grosor. Los niveles de profundidad se denominan B, C y D, siendo el primero el más superficial y el último el más profundo.

4.1. CELENTERADOS (= CNIDARIOS)

Tubularia sp. (figs. 9 *a* y *b*)

El ciclo de fijación de esta especie presenta claras diferencias en las dos zonas consideradas. En el sistema externo se observa una colonización de poca importancia, restringida al mes de abril. En el sistema interno, en cambio, el ciclo de fijación se extiende de diciembre a abril, con un período de intensa colonización entre diciembre y febrero.

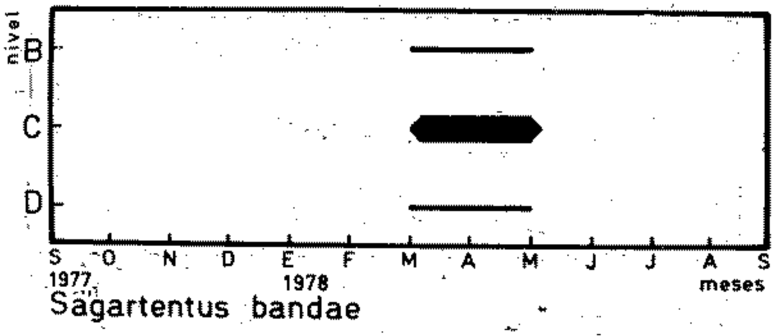

FIG. 10 *a.*—Ciclo de fijación, sistema externo.

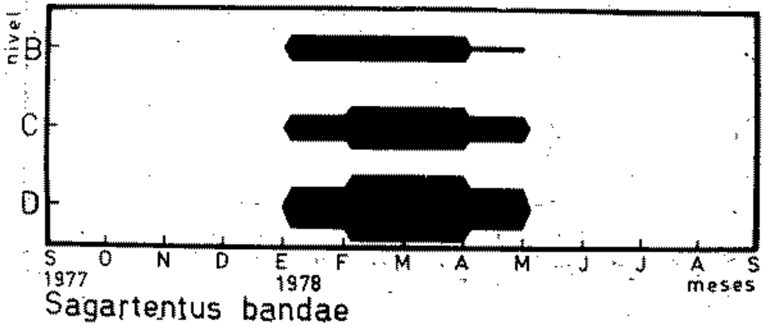

FIG. 10 *b.*—Ciclo de fijación, sistema interno.

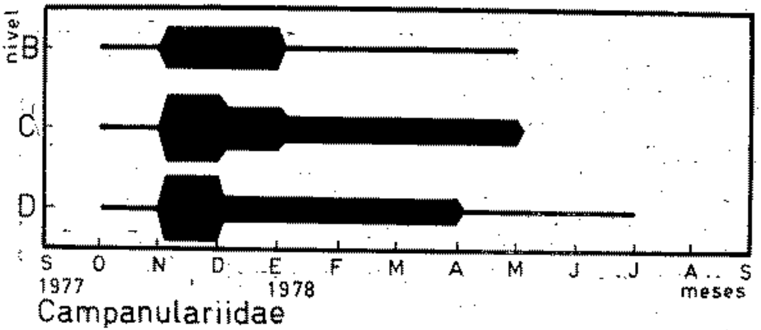

FIG. 11 *a.*—Ciclo de fijación, sistema externo.

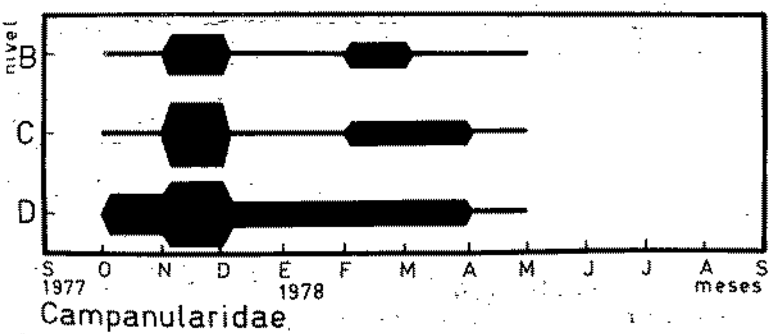

FIG. 11 *b.*—Ciclo de fijación, sistema interno.

FIG. 12 *a*.—Ciclo de fijación, sistema externo.

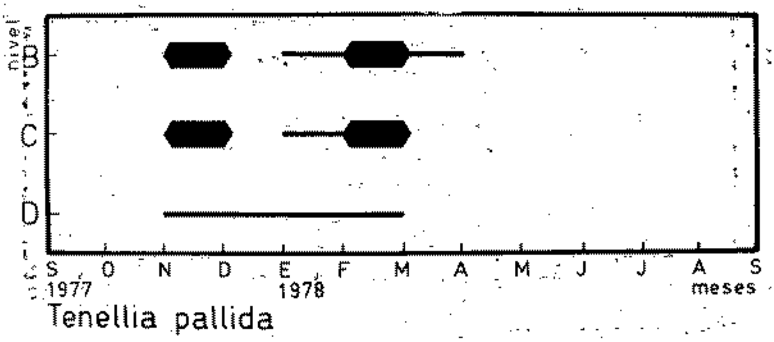

FIG. 12 *b*.—Ciclo de fijación, sistema interno.

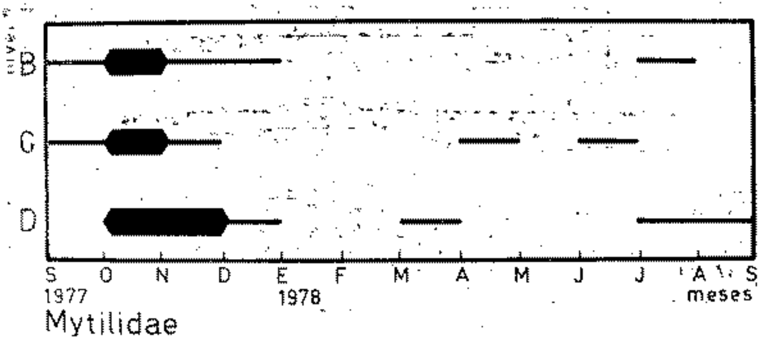

FIG. 13 *a*.—Ciclo de fijación, sistema externo.

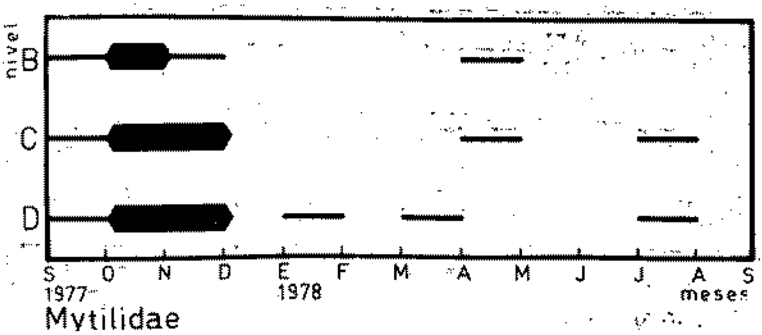

FIG. 13 *b*.—Ciclo de fijación, sistema interno.

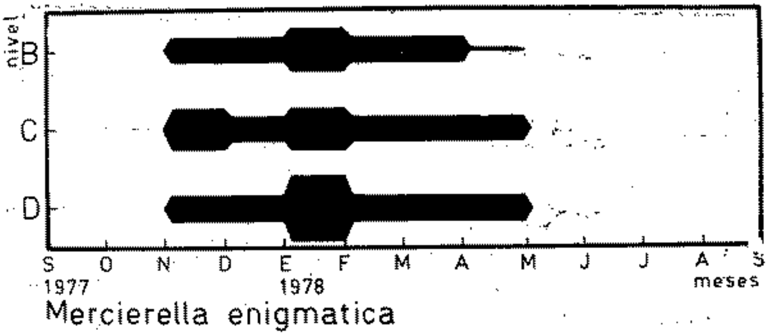

FIG. 14 *a.*—Ciclo de fijación, sistema externo.

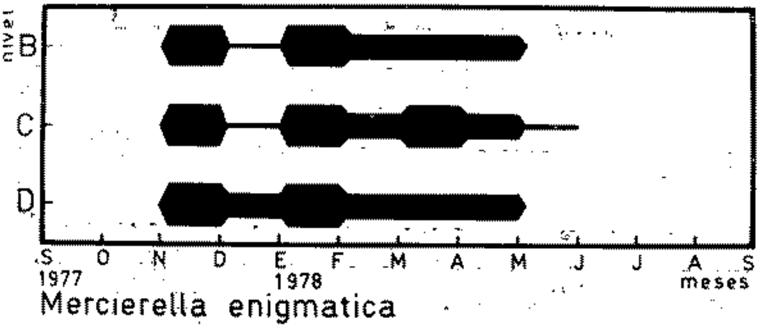

FIG. 14 *b.*—Ciclo de fijación, sistema interno.

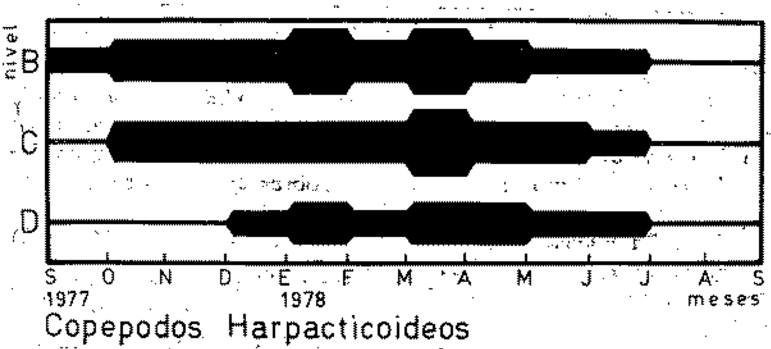

FIG. 15 *a.*—Ciclo de fijación, sistema externo.

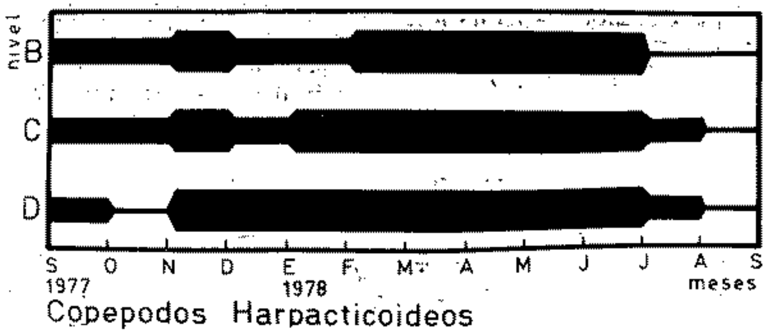

FIG. 15 *b.*—Ciclo de fijación, sistema interno.

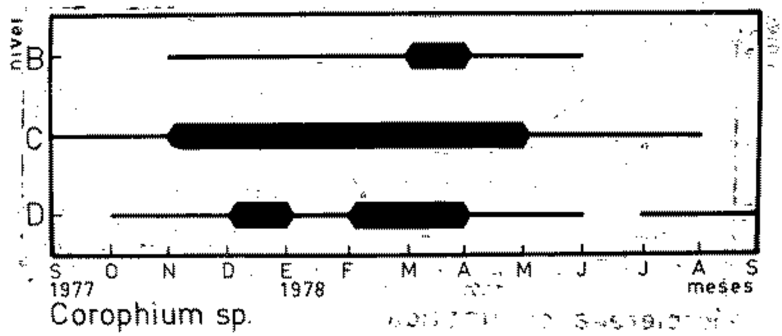

FIG. 16 *a*.—Ciclo de fijación, sistema externo.

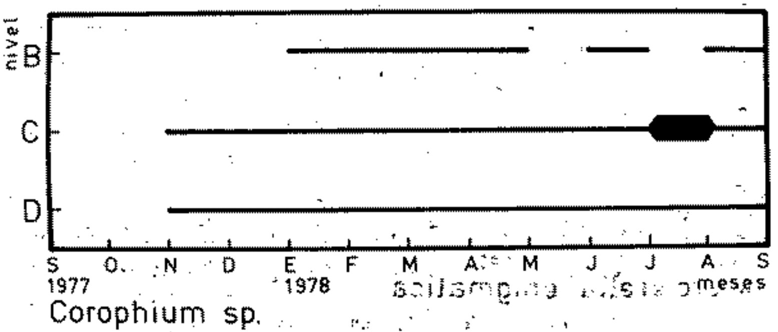

FIG. 16 *b*.—Ciclo de fijación, sistema interno.

Las diferencias observadas deben atribuirse a la distinta intensidad luminosa que caracteriza a cada uno de los sectores. Ello coincide, además, con lo observado en ambientes naturales, en donde *Tubularia* coloniza preferentemente zonas de baja iluminación. Debido a dicha característica, este organismo puede desempeñar un papel importante dentro de los sistemas de refrigeración, y en inspecciones realizadas en años anteriores fue detectado en forma abundante. Sin embargo, debido a su ciclo de vida breve y a la ausencia de un exoesqueleto calcáreo resulta menos perjudicial que otras especies registradas en la zona.

Sagartentus bandae (fig. 10 *a* y *b*)

Este antozoario presenta también marcadas diferencias en su ciclo de fijación en ambas zonas. En el sistema externo, la fijación se extiende desde marzo hasta mayo y se produce en bajas densidades. En el sistema interno, el ciclo de colonización es más amplio, extendiéndose desde enero hasta mayo; la colonización se produce en alta densidad, principalmente en el panel más profundo. También en este caso el factor determinante de las diferencias observadas es probablemente la luz.

Campanulariidae (fig. 11 *a* y *b*)

Estos hidrozoos presentan ciclos de fijación semejantes en ambas zonas de estudio, tanto en densidad como en duración. La colonización se extiende desde octubre hasta mayo/julio, con un período de máxima intensidad, correspondiente al mes de noviembre; se trata, pues, de organismos eurioicos, capaces de desarrollarse en condiciones ambientales muy variables.

4.2. MOLUSCOS

Tenellia pallida (fig. 12 *a* y *b*)

Este nudibranquio vive íntimamente asociado a los campanuláridos, en virtud de que

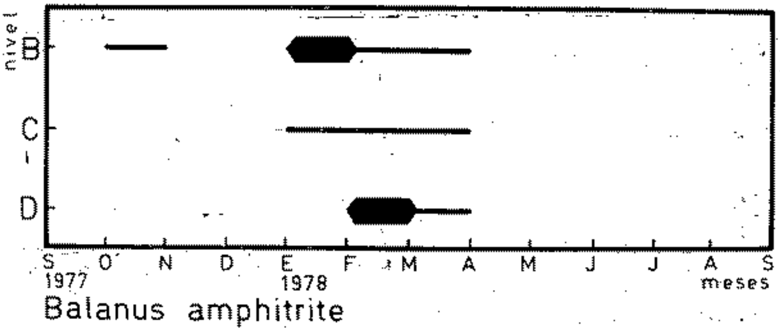

FIG. 17.—Ciclo de fijación, sistema externo.

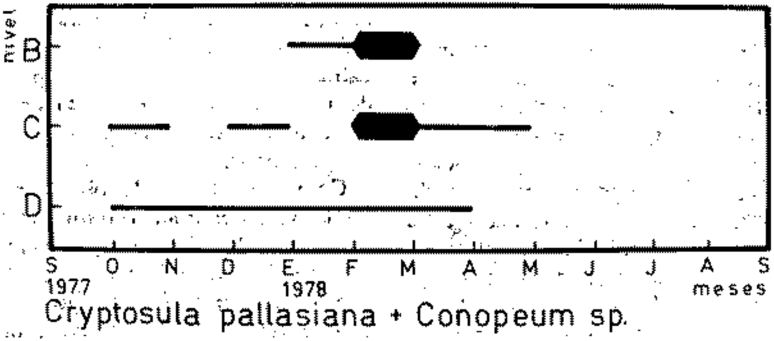

FIG. 18 *a*.—Ciclo de fijación, sistema externo.

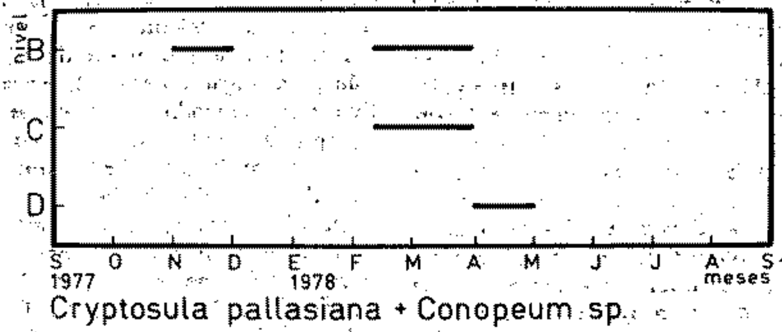

FIG. 18 *b*.—Ciclo de fijación, sistema interno.

basa su alimentación exclusivamente sobre estos hidrozoos; en ellos encuentra, además, refugio y deposita sus puestas. Por este motivo, el ciclo de *Tenellia pallida* siempre es coincidente con el de los campanuláridos. El mismo se extiende entre noviembre y agosto, es decir, que se inicia poco después del comienzo de la fijación de campanuláridos y finaliza poco tiempo antes.

La fijación difiere levemente en ambas zonas, principalmente en lo que se refiere a abundancia.

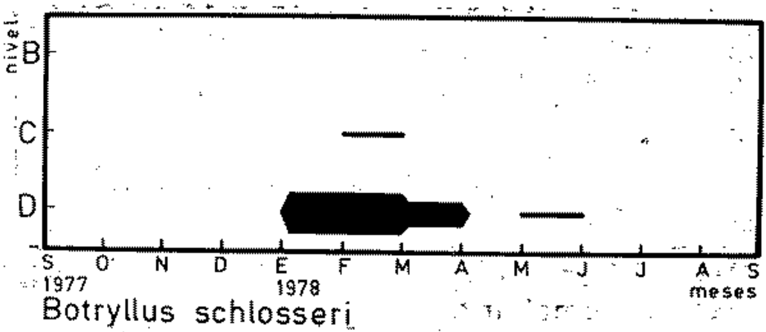

FIG. 19.—Ciclo de fijación, sistema externo.

Mytilidae (fig. 13 *a* y *b*)

Los ejemplares de esta familia pertenecen a dos de las especies presentes en el área: *Mytilus platensis* y *Brachydontes rodriguezi*. El análisis de las muestras provenientes de paneles mensuales no ha permitido diferenciarlas, ya que se trataba en todos los casos de ejemplares juveniles; por tal motivo se las ha graficado en forma conjunta. Cabe señalar que ambas especies han sido registradas en cantidades abundantes en el sistema de refrigeración de la central durante inspecciones realizadas en años anteriores.

Estos organismos pueden ser considerados entre los más perjudiciales de las comunidades incrustantes locales, junto con otros que se mencionan más adelante.

El ciclo de fijación se extiende a lo largo de casi todo el año, con algunas interrupciones, tanto en la zona interna como en la externa, pero el período de colonización más intensa transcurre entre octubre y diciembre; durante el resto del año, ambas especies se fijan en forma esporádica y en bajas densidades.

Como puede observarse en los gráficos correspondientes, las diferencias entre las dos zonas son mínimas y poco significativas.

4.3. ANÉLIDOS

Mercierella enigmatica (fig. 14 *a* y *b*)

Constituye, sin duda, el organismo más perjudicial de las comunidades incrustantes locales. Su presencia tan abundante en el puerto de Quequén se debe a las condiciones ambientales que prevalecen en la zona y que resultan favorables para el desarrollo de esta especie, tales como las bajas salinidades y la moda calma. Durante el presente período su ciclo de fijación se ha extendido entre noviembre y mayo, siendo los registros semejantes en ambos sistemas.

Coincidiendo con lo observado en el puerto de Mar del Plata durante varios años consecutivos, el ciclo de reproducción y fijación de *Mercierella enigmatica* está condicionado por la temperatura del agua (1). La fijación comienza en noviembre/diciembre, cuando la temperatura media del agua se aproxima a los 15° C, intensificándose la colonización con el incremento de la temperatura durante la época estival y prolongándose mientras la temperatura no desciende de los 15° C.

Este control por parte de la temperatura sólo tiene lugar durante el proceso reproductivo y el desarrollo de las etapas larvales; los ejemplares adultos son capaces de soportar sin mayores inconvenientes un amplio intervalo de variación térmica.

Debido a esta relación tan estrecha entre el ciclo de fijación y la temperatura del agua es posible, en base al registro de este último factor, predecir el momento de inicio de la colonización y programar en forma más precisa el sistema de control a aplicar.

4.4. CRUSTÁCEOS

Copépodos harpacticoideos (fig. 15 *a* y *b*)

Se trata de organismos que se integran a la comunidad incrustante durante las primeras

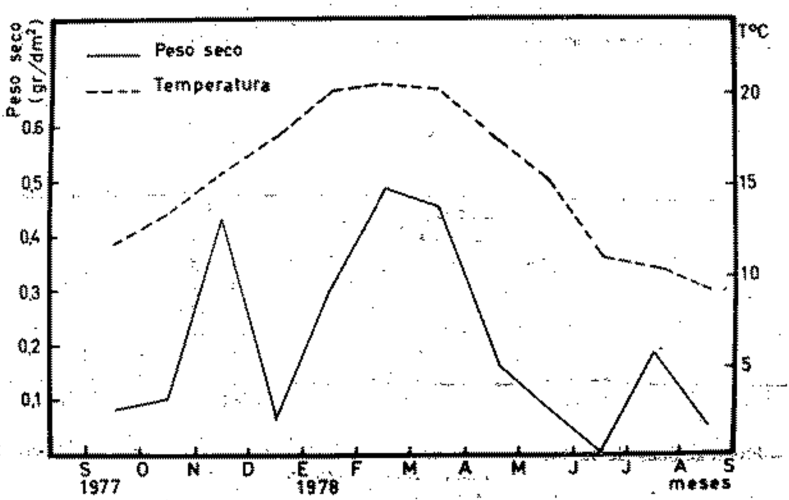

FIG. 20.—Fluctuaciones de la temperatura media del agua y de la biomasa en paneles mensuales (promedio de los valores obtenidos en los niveles B, C y D), sistema externo.

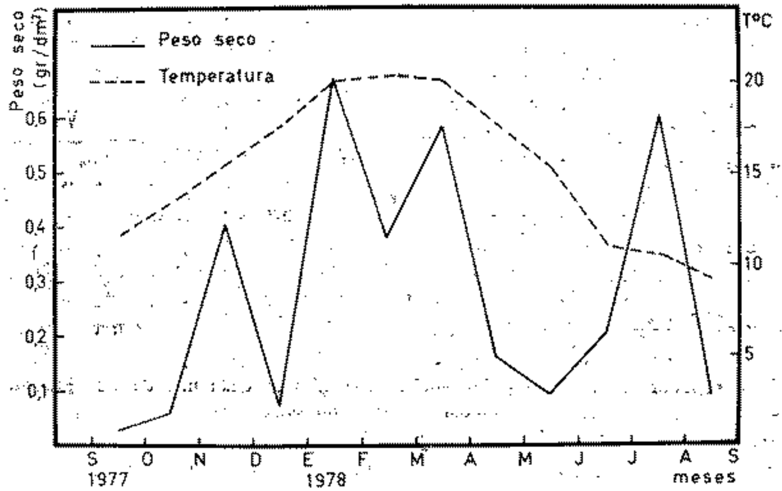

FIG. 21.—Fluctuaciones de la temperatura media del agua y de la biomasa en paneles mensuales (promedio de los valores obtenidos en los niveles B, C y D), sistema interno.

etapas sucesionales, constituyendo posteriormente una importante fuente de alimentación para otros integrantes de la misma.

Su ciclo de fijación se extiende a lo largo de todo el año, produciéndose la colonización en forma bastante intensa y uniforme; no se aprecian diferencias importantes entre las dos zonas estudiadas ni tampoco se detectan preferencias batimétricas.

Corophium sp. (fig. 16 *a* y *b*)

Este anfípodo se fija a los sustratos experimentales a lo largo de casi todo el año. Existen, sin embargo, ciertas diferencias en la fijación registrada en ambos sistemas; el externo suele ser colonizado en mayor densidad.

La acción perjudicial de este organismo radica fundamentalmente en sus hábitos tubíco-

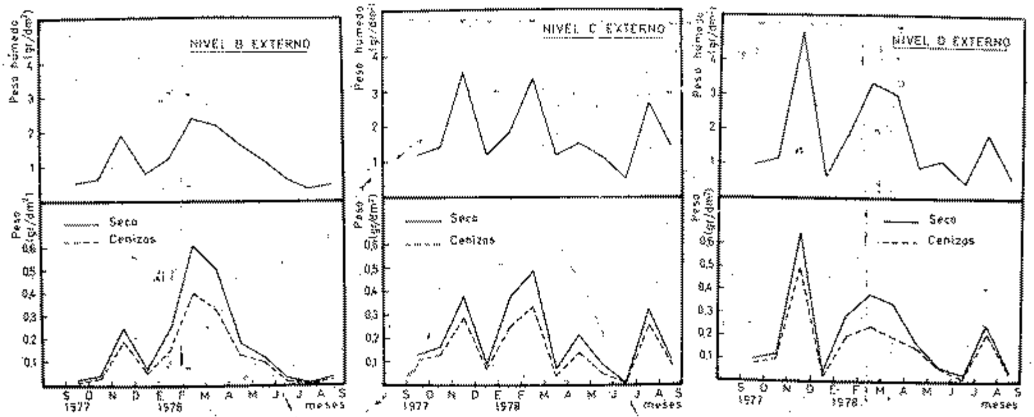

FIG. 22.—Fluctuaciones de la biomasa de paneles mensuales en cada uno de los niveles de profundidad, sistema externo.

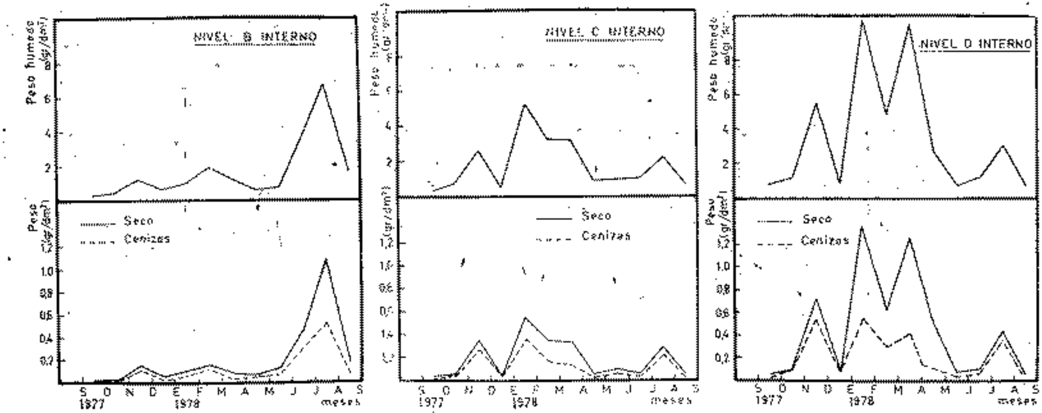

FIG. 23.—Fluctuaciones de la biomasa de paneles mensuales en cada uno de los niveles de profundidad, sistema interno.

las, ya que sus tubos pueden formar tapices de considerable espesor y promover a su vez el asentamiento de otras especies.

Balanus amphitrite (fig. 17)

Constituye uno de los componentes incrustantes más agresivos y resistentes a los tóxicos. Sin embargo, se ignora el papel que esta especie desempeña en los sistemas de refrigeración de la central, ya que durante la presente experiencia *Balanus amphitrite* ha sido registrado exclusivamente en el sistema de paneles externos. En dicha zona se ha fijado en baja densidad y con un ciclo que se extiende entre enero y abril.

En otras áreas portuarias (Puerto Belgrano y Mar del Plata), los cirripedios presentan un ciclo de fijación más prolongado, ligado directamente con el aumento de temperatura de las aguas, así como también una mayor abundancia (1, 2, 5, 9).

Su ausencia en los paneles internos durante la presente oportunidad no significa que esta especie sea incapaz de colonizar las tuberías de refrigeración, ya que ha sido registrada en dicha zona durante inspecciones realizadas en años previos, si bien en bajas densidades.

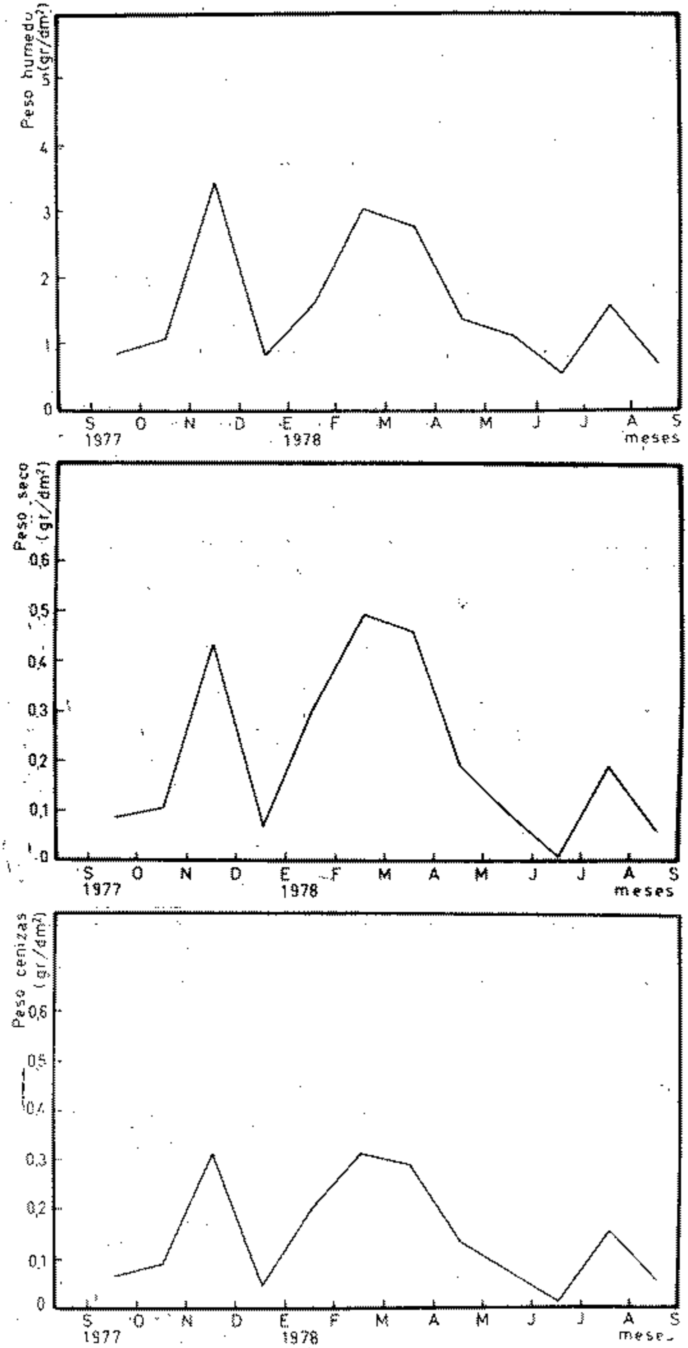

FIG. 24.—Fluctuaciones de la biomasa de paneles mensuales (promedio de los valores obtenidos en los niveles B, C y D), sistema externo.

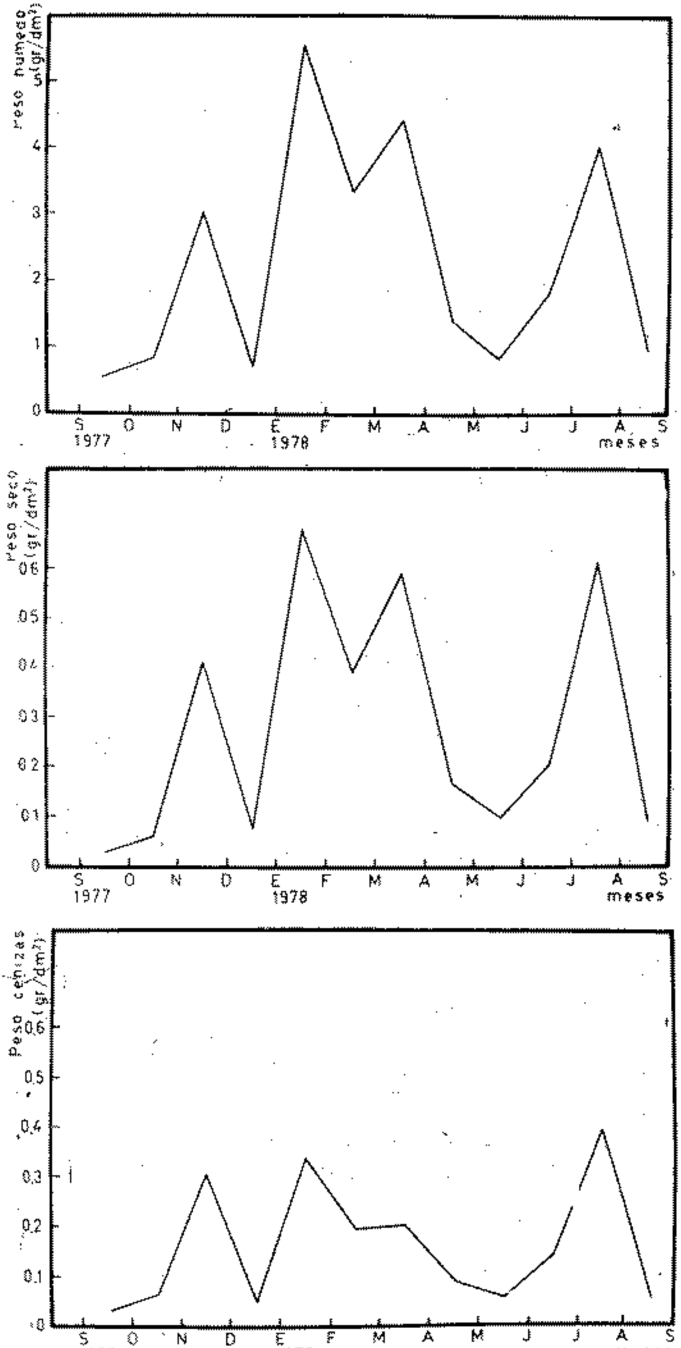

FIG. 25.—Fluctuaciones de la biomasa de paneles mensuales (promedio de los valores obtenidos en los niveles B, C y D), sistema interno.

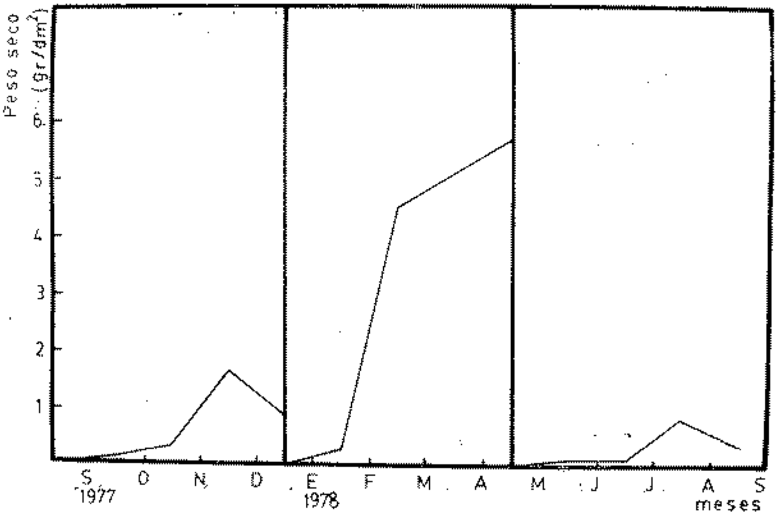

FIG. 26.—Fluctuaciones de la biomasa de paneles acumulativos (promedio de los valores obtenidos en los niveles B, C y D), sistema externo.

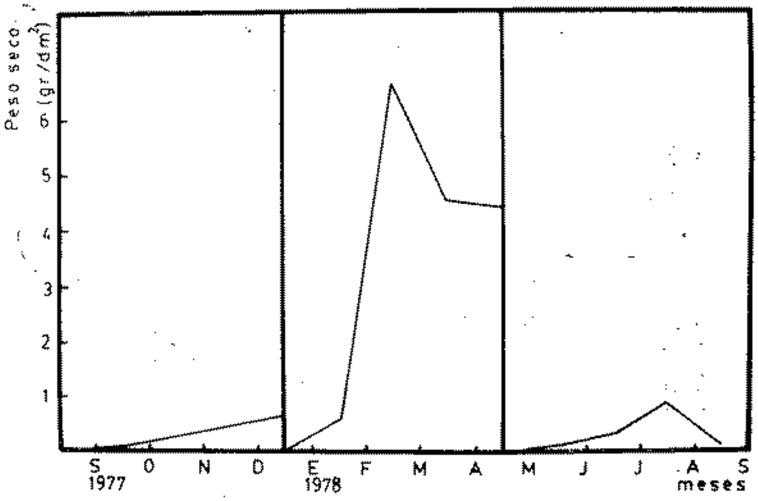

FIG. 27.—Fluctuaciones de la biomasa de paneles acumulativos (promedio de los valores obtenidos en los niveles B, C y D), sistema interno.

4.5. BRIOZOOS

Cryptosula pallasiana + *Conopeum* sp. (figs. 18 *a* y *b*)

Estas dos especies de briozoos incrustantes han sido graficadas conjuntamente. Durante el presente ensayo, su ciclo de fijación se ha extendido entre octubre/noviembre y marzo. Ambas colonizaron tanto el sistema externo como el interno, en baja densidad; en el primero, la colonización ha sido levemente más intensa y con menos interrupciones.

4.6. TUNICADOS

Botryllus schlosseri (fig. 19)

Este tunicado colonial ha sido registrado exclusivamente en el sistema externo, por lo cual

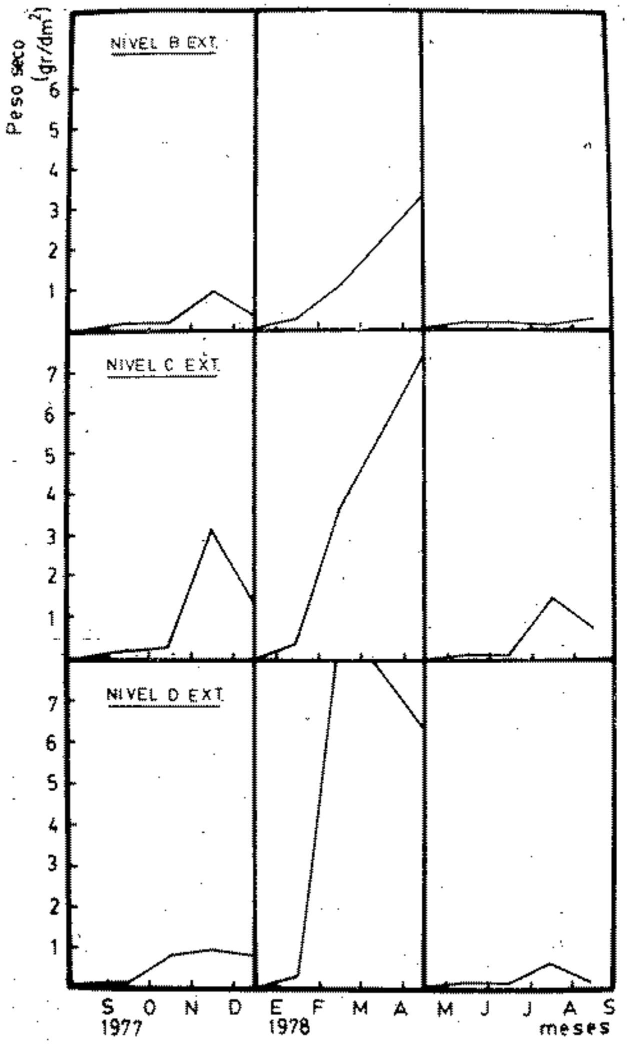

FIG. 28.—Fluctuaciones de la biomasa de paneles acumulativos en cada uno de los niveles de profundidad, sistema externo.

puede deducirse que las condiciones reinantes en los sistemas de refrigeración no son propicias para su desarrollo.

Presenta un ciclo de fijación que se extiende entre enero y abril y con una fijación complementaria en el mes de mayo. Muestra claras preferencias por colonizar el panel ubicado a mayor profundidad (panel D).

Tal como ocurre con otras especies, su desarrollo se ve favorecido por las bajas salinidades. En Puerto Belgrano, donde también se registran valores de salinidad relativamente bajos, *Botryllus schlosseri* constituye uno de los principales tunicados de las comunidades incrustantes.

5. FLUCTUACIONES DE LA BIOMASA EN LAS COMUNIDADES INCRUSTANTES

Con la finalidad de determinar las características de las comunidades incrustantes des-

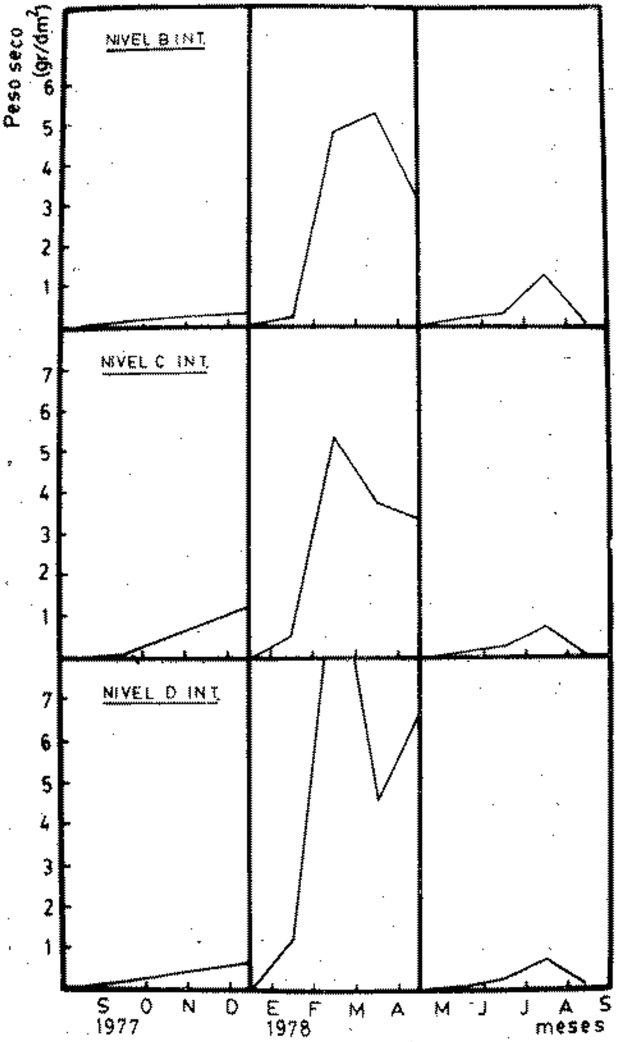

FIG. 29.—Fluctuaciones de la biomasa de paneles acumulativos en cada uno de los niveles de profundidad, sistema interno.

de un punto de vista cuantitativo, se analizaron los valores de biomasa registrados tanto sobre paneles mensuales como acumulativos. A través de los primeros se obtuvieron valores de biomasa alcanzados luego de treinta días de inmersión a lo largo de un período anual. De acuerdo al programa de muestreo aplicado en este ensayo, los paneles acumulativos brindaron datos de biomasa de la comunidad a lo largo de tres períodos cuatrimestrales sucesivos de inmersión.

Los estudios realizados en otras áreas portuarias de la provincia de Buenos Aires han indicado claramente la influencia que ejerce la temperatura del agua sobre la biomasa y grado de complejidad de las incrustaciones en los paneles de tipo mensual (1, 9). Vale decir que durante los períodos de elevada temperatura se registran los máximos valores de biomasa, mientras que a temperaturas mínimas corresponden valores muy bajos de biomasa y estados poco evolucionados de la comunidad.

Observando los gráficos que relacionan biomasa (expresada en peso seco) con temperatura media del agua (figs. 20 y 21) de los sistemas externo e interno se ve que se producen fluctuaciones en los valores de biomasa que se apartan del esquema observado en otros puertos (puerto de Mar del Plata y Puerto Belgrano). La biomasa correspondiente a los paneles externos (fig. 20) va ascendiendo junto con la temperatura, pero entre diciembre y enero se produce un brusco descenso que no se correlaciona con los valores de temperatura del agua. Este descenso es real y no es el resultado de promediar los valores de biomasa de los distintos niveles de profundidad; analizando la figura 22 puede observarse que en cada uno de los paneles queda registrado este descenso en la biomasa.

Este fenómeno se ha debido, en parte, a que entre noviembre y diciembre se produjo una intensa fijación de *Mercierella enigmatica*, descendiendo bruscamente durante el mes siguiente para volver a incrementarse durante enero/febrero. Estas fluctuaciones, que han repercutido sobre los valores de biomasa, pueden haberse debido a circunstancias muy diversas; entre ellas cambios bruscos, no registrados, en las condiciones ambientales.

A partir del mes de enero, la biomasa aumenta hasta alcanzar sus valores máximos en coincidencia con la máxima temperatura de febrero/marzo, para luego descender nuevamente junto con la temperatura. Sin embargo, entre julio y agosto se produce un incremento que también resulta inesperado considerando las bajas temperaturas de esos meses.

Este pico no responde a un incremento real de la biomasa, sino que se debe a la gran cantidad de detritus que se acumula sobre los paneles, como consecuencia de un mayor arrastre de sedimentos por grandes crecidas del río.

El valor máximo de biomasa (expresado en peso seco) en el sistema externo es de aproximadamente 0,5 g/dm², valor que resulta bajo si se lo compara con los registrados en el puerto de Mar del Plata (3,48 g/dm² para 1973-1974 y 6,75 g/dm² para 1976-1977) (9).

Analizando la curva de biomasa de los paneles internos en relación con la temperatura (figura 21) se observa que se produce el descenso ya mencionado entre diciembre y enero. Este descenso queda también registrado en cada uno de los niveles de profundidad (figura 23). En cuanto al incremento que se observa entre julio y agosto, también se repite en cada uno de los paneles, pero en forma más intensa en el panel B.

Con respecto al valor máximo de biomasa (expresado en peso seco) en el sistema interno, se observa que es levemente más alto que el registrado en el sistema externo (aproximadamente 0,65 g/dm²).

En cuanto a los paneles acumulativos, en el sistema externo (fig. 26) puede observarse durante el primer cuatrimestre que la biomasa de la comunidad se va incrementando paulatinamente hasta llegar a un máximo al tercer mes de inmersión, seguido de un descenso en el cuarto mes. Durante el segundo cuatrimestre se produce un incremento muy importante en la biomasa al segundo mes de inmersión, que culmina en un valor máximo de aproximadamente 5,6 g/dm² (peso seco) al completarse el cuatrimestre. En el tercer cuatrimestre, el incremento de biomasa es más lento, con un máximo al tercer mes de inmersión y un leve descenso en el último mes.

De los tres niveles de profundidad analizados, el valor máximo de biomasa se obtiene en el panel D durante el segundo cuatrimestre (fig. 28).

En el sistema interno (fig. 27), durante el primer cuatrimestre la biomasa de la comunidad va aumentando en forma paulatina hasta llegar a un valor máximo al final del período de inmersión. Durante el segundo cuatrimestre, el valor máximo de biomasa se obtiene a los 60 días de inmersión (aproximadamente 6,9 g/dm² en peso seco), produciéndose un paulatino descenso durante los dos últimos meses. En el tercer cuatrimestre, el incremento de biomasa se produce más lentamente, llegando a un valor máximo al tercer mes de inmersión para luego descender durante el cuarto y último mes.

Al igual que en el sistema externo, el valor máximo de biomasa corresponde al panel D y se produce durante el segundo cuatrimestre (figura 29).

El análisis comparativo de los sistemas externo e interno indica que no existen mayores diferencias entre ambos.

Según lo observado en el puerto de Mar del Plata y Puerto Belgrano, la biomasa de paneles acumulativos guarda una relación menos estrecha con el factor temperatura, ejerciendo una influencia directa exclusivamente durante los primeros meses de evolución de la comunidad (1, 9). Dado que durante el presente ensayo los paneles acumulativos han permanecido sumergidos por períodos cuatrimestrales, la influencia de la temperatura resulta bastante evidente. Es por ello que en todos los niveles de profundidad estudiados los valores más altos de biomasa corresponden al período estival, mientras que los mínimos se producen en los meses más fríos.

Cabe señalar que el pico que se registra durante el tercer cuatrimestre responde a una sobrevaloración de la biomasa acumulada, debido a la presencia de abundante detritus depositado durante grandes crecientes del río, ya señaladas anteriormente. Por la metodología empleada resulta imposible separar ambas fracciones en forma adecuada.

Los valores de biomasa obtenidos durante este ensayo sobre paneles acumulativos en períodos cuatrimestrales han resultado notoriamente inferiores a los obtenidos en el puerto de Mar del Plata y Puerto Belgrano en períodos semejantes. Esto no significa que en períodos más prolongados de inmersión la comunidad no pueda alcanzar valores de biomasa comparables a los de los otros puertos mencionados.

6. CONSIDERACIONES FINALES

La zona de Puerto Quequén se caracteriza por presentar condiciones hidrológicas particulares en virtud de la influencia recíproca que se establece entre masas de agua de origen continental y marino. Estas características de tipo estuarial hacen que se produzcan grandes variaciones en ciertos factores ambientales, como la salinidad, a lo largo del día y del año. Dichas condiciones favorecen, a su vez, el notable desarrollo de las poblaciones locales de *Mercierella enigmatica*, una de las especies más perjudiciales para los sistemas de refrigeración de la central termoeléctrica emplazada en la zona.

La calidad de las aguas portuarias, en cambio, resulta superior a la de otros puertos, en virtud del limitado desarrollo industrial alcanzado hasta el momento y el buen sistema de renovación de las mismas.

La comunidad incrustante analizada, si bien presenta características peculiares de la zona, probablemente resulte más afín a la de Puerto Belgrano que a la de Mar del Plata.

Los ciclos de fijación de las principales especies estudiadas permiten tener una idea de las épocas del año en que los organismos colonizan los sustratos artificiales y el grado de intensidad con que pueden hacerlo. A su vez, el análisis paralelo de fijación en los sistemas externo e interno ha permitido detectar cuáles son las especies que encuentran condiciones propicias para su desarrollo en los sistemas de refrigeración. Esta información resulta de especial interés para el régimen que deberá seguir la central termoeléctrica en la aplicación de sistemas de control antiincrustante.

De las especies analizadas, las que podrían encontrarse con mayor frecuencia en los sistemas de refrigeración serían *Mercierella enigmatica, Brachydontes rodriguezi, Mytilus platensis, Tubularia* sp. y *Campanulariidae*. En términos generales, los ciclos de fijación de estos organismos están influenciados por la temperatura del agua, comenzando con el calentamiento de las mismas en primavera y prolongándose hasta su enfriamiento durante el otoño. El desarrollo posterior de los mismos, en cambio, suele estar al margen de las fluctuaciones térmicas del agua.

El panorama general de Puerto Quequén con respecto a los valores de biomasa registrados sobre paneles experimentales ha resultado bastante complejo y se aparta, en cierta medida, de lo observado en el puerto de Mar del Plata y Puerto Belgrano. Ello se debe, fundamentalmente, a los cambios que se producen, tanto en la temperatura como en la salinidad, y al aporte de sedimentos durante períodos de grandes crecientes del río Quequén.

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EFFECT OF MICROFOULING ON HEAT TRANSFER EFFICIENCY

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USA

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HAWAII

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GULF OF MEXICO

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ABSTRACT

Field experiments, performed at Keahole Point, Hawaii and in the Gulf of Mexico, were designed to determine the relationship between decreased heat transfer efficiency and the accumulation of corrosion and/or biofouling films on heat exchanger surfaces. The sample tubes were maintained under conditions simulating those of an Ocean Thermal Energy Conversion (OTEC) system and data from the two sites have been compared. Seawater flowed through 2.54 (internal diameter) metal tubes at approximately 1.8 m sec^{-1}. Four types of tubes were used: 5052 aluminum (Al), grade 2 titanium (Ti), 90-10 copper-nickel (Cu-Ni) and Allegheny-Ludlum 6X stainless steel (SS).

All surfaces were colonized by microorganisms, though colonization of the Cu-Ni surface was initially retarded. Total film weight was greatest for the Al and Cu-Ni surfaces which were characterized by corrosion as well as microbial fouling. The total organic carbon: total nitrogen ratios of the fouling films from Ti, Al, SS and Cu-Ni, 4.2, 4.0, 4.8 and 7.9 respectively, remained constant throughout the experiment. The degradation of heat transfer efficiency due to the formation of fouling layers on Ti and SS is neither linear nor a simple exponential function. A microfouling model is proposed for corrosion-resistant surfaces that is consistent with field observations.

INTRODUCTION

Ocean Thermal Energy Conversion (OTEC) is a concept which employs the difference in

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temperature between warm surface waters and cold deep waters to generate energy. In marine environments, the temperature differential is only about 20° C, thus, the efficiency of such a system is quite low. Operation of an OTEC system requires the maintenance of efficient heat exchangers. Insulating material in the form of fouling layers less than 100 μm thick can render such a system inoperative. Several processes can contribute to the formation of such layers: formation of corrosion products, deposition of inorganic salts, adsorption of dissolved organic material, colonization by microorganisms and the accumulation of their metabolic products, and the adhesion of detritus. The contribution of the various factors is dependent on the type of metal used in the heat exchanger, flow conditions, geographical location of exposure and environmental parameters. OTEC experiments were conducted in the Gulf of Mexico (GOM) and Hawaii (HI) to collect fouling data and to correlate those data with heat transfer efficiency.

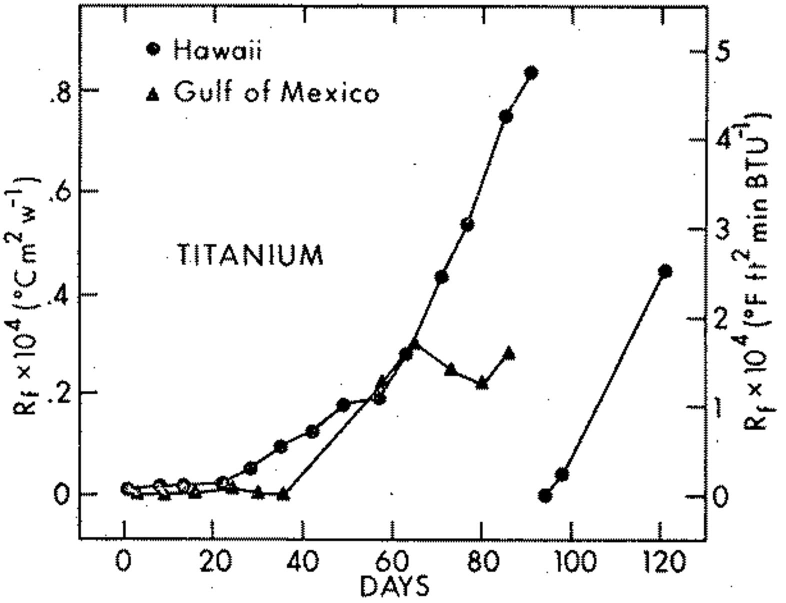


Fig. 1 *a*.—R_f vs. time for data from the two experimental sites for Ti.

METHODS AND MATERIALS

Details of the construction, operation, sample collection, and analytical procedures of the GOM and HI experiments have been previously presented (Liebert *et al.*, 1979; Little *et al.*, 1979). The HI experiments took place 300 meters off the coast of Keahole Point, HI; the GOM experiments 257 km due west of Tampa, Fl. The alloys used for the heat exchangers were 5052 aluminum (Al), grade 2 titanium (Ti), Allegheny-Ludlum 6X stainless steel (SS) and CDA 706 copper-nickel (Cu-Ni). Except for occasional malfunctions, seawater from the upper mixed layer flowed through 2.5 cm (i.d.) tubes continuously at a nominal flow rate of 2 meters per second.

The instruments used for the measurement of heat transfer resistance (R_f) were designed at Carnegie-Mellon University (Fetkovich, 1977) and modified by Argonne National Laboratory. R_f is expressed as hr. ft^2 °F/BTU units. To convert to international R_f units

(°C m^2w^{-1}) multiply R_f values by 0.176. R_f is defined as the difference between 1/h where h is the measured heat transfer coefficient at any given time and the initial value of 1/h. Reference 2 discusses the corrections, based on water temperature and flow rate, used to calculate the heat transfer coefficient and fouling factor.

A modified M.A.N. brush (NÜBEL, 1977) was passed through the tubes of the HI experiment during flow to clean the fouling layers from the tube surfaces. Cleaned tubes were allowed to refoul. Sections from the flow systems of the two experiments were removed periodically and the following constituents and properties of the fouling layers quantified: total organic carbon, total nitrogen, dry film weight, wet film thickness and surface topography.

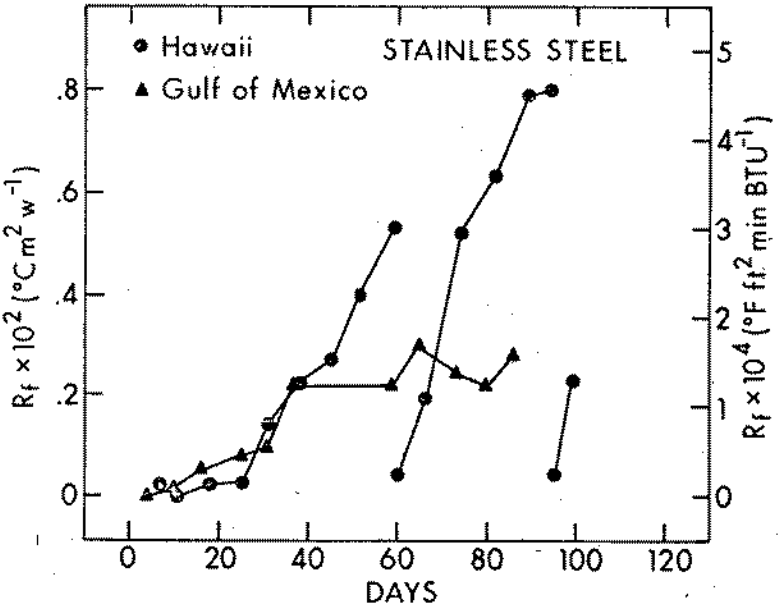


FIG. 1 *b*.—R_f vs. time for data from the two experimental sites for SS.

RESULTS AND DISCUSSION

Increased heat transfer resistance (R_f) as a function of time and alloy for both exposure sites is given in Figure 1 (a-d). There was a briefer lag period before increases in R_f could be measured for all surfaces exposed at the HI site as compared to the lag period experienced by the surfaces exposed in the GOM. There was no apparent lag period for the Cu-Ni surfaces at either site. Titanium surfaces consistently exhibited the longest lag period before there was measurable loss of heat transfer efficiency due to fouling.

Heat transfer resistance, total organic carbon (TOC) and total nitrogen (TN) are plotter against exposure time for all alloys in Figure 2 (a-d). The scales of the ordinate were chosen such that the TOC and TN data for the titanium tube would superimpose on that of R_f. Ti and SS have similar chemical properties; neither corrodes vigorously in seawater (LAQUE, 1979), nor is either toxic to microorganisms (MARSZALEK, 1979). One would therefore expect the two materials to exhibit nearly identical fouling and loss of heat transfer efficiency. The results shown in Figure 2 indicate that differences did exist.

One macroscopic difference was the topography of the two surfaces as received from the manufacturer. The inner surface of the SS tubes was marked with deep extrusion lines; these were absent in the titanium tubes (Fig. 3 a and b). It is unlikely that the nature of the microflora on the two metal surfaces is responsible for the differences observed in the R_f data. Differences were not detected in SEM micrographs of the two fouled surfaces.

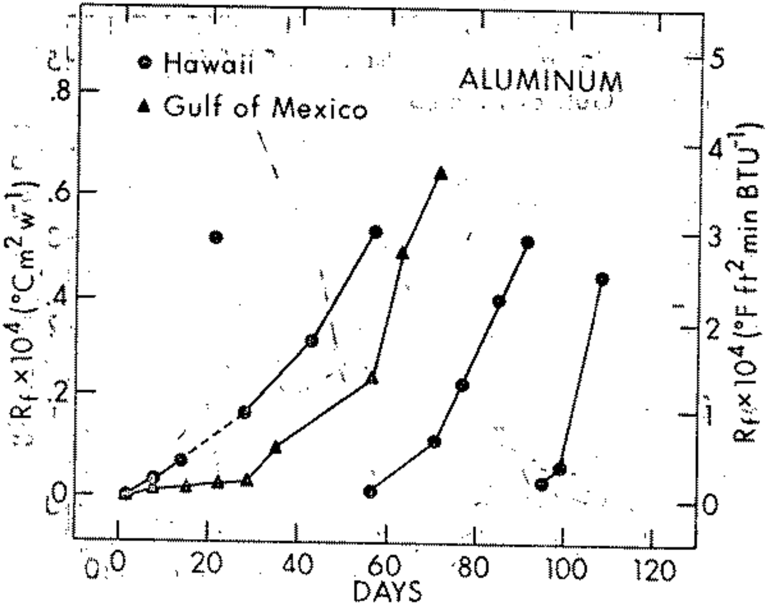


FIG. 1 *c*.—R_f vs. time for data from the two experimental sites for Al.

The biofilm on the stainless steel surface did obscure the surface roughness after 78 days (Figure 4).

Wet film thickness measurements were comparable for the period of investigation (LITTLE *et al.*, 1979). TN:TOC ratios (Fig. 5) and dry film weight:TOC ratios (Fig. 6) in the fouling layers from the Ti and SS surfaces are very similar. The ratio of TOC to dry film weight was approximately 1:8 for both Ti and SS (Table 1) indicating that substantial amounts of inorganic materials are present in the fouling films. As stated previously, neither of those materials corrodes appreciably in seawater. The mucopolysaccharide secretions and microorganisms do chelate substantial amounts of inorganic salts from seawater (SIEGEL, 1971).

One explanation for the differing heat transfer responses observed for the two metals may be related to the surface roughness observed for the stainless steel. Water may become entrapped in the grooves of the stainless steel surface as the overlying biofilm develops, providing greater insulating effects. Thus, films with identical TOC, TN and wet film thickness would exhibit differing heat transfer responses.

Plots of R_f vs. dry film weight (Fig. 7) and R_f vs. total organic carbon (Fig. 8) for SS, Ti and Al indicate a linear relationship between the two. There also appears to be a linear relationship between R_f and TOC for SS and Ti. Such a correlation is not apparent for Al and Cu-Ni data. It appears (Fig. 1) that for approximately the first 20 days the R_f of the Al surface is independent of both TOC and TN. It is during this period that the corrosion layer increases rapidly (LITTLE and LAVOIE, 1979). After about three weeks, the increase

TABLE 1

RATIOS OF TOTAL ORGANIC CARBON TO R_f AND DRY FILM WEIGHT FROM STAINLESS STEEL AND TITANIUM TUBES

	HAWAII		GULF OF MEXICO	
Site	*Ti*	*SS*	*Ti*	*SS*
Organic C ($\mu g\ cm^{-2}$)	25.2	13.1	4.6	4.7
Film Dry Weight ($mg\ cm^{-2}$)	3.1	1.8	—	—
$R_f \times 10^4$ ($^\circ F\ ft^2\ min\ BTU^{-1}$)	1.6	2.3	0.5	0.93
Ratio (C/R_f)	15.8	5.7	9.2	5.1
Ratio (C/Dry Weight)	8.1	7.3	—	—

Data for Gulf of Mexico are taken at 48 days; those for Hawaii are the arithmetic mean taken before the first cleaning.

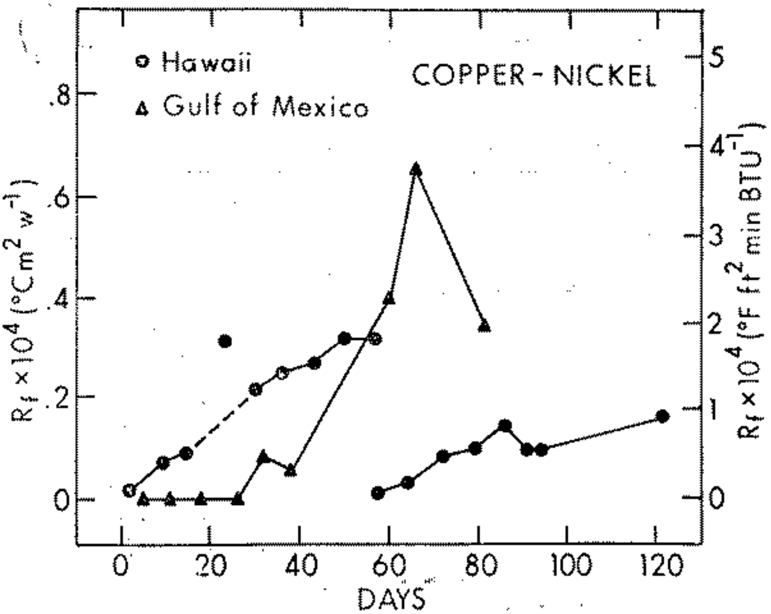


FIG. 1 *d.*—R_f vs. time for data from the two experimental sites for Cu-Ni.

in R_f can be partially ascribed to TOC, and hence, biofilm formation. Corrosion of the Al surface during the first three weeks does adversely effect heat transfer efficiency.

The dry film weight of the Cu-Ni is an order of magnitude greater than that for the other metal surfaces (Fig. 7). The increase in R_f with time for the Cu-Ni surface is largely due to the formation of a corrosion film. No correlation can be made between R_f and TOC or TN (Fig. 9 d). TOC: TN ratios for the Cu-Ni is substantially greater (Table 2) than that for the other materials (Fig. 9 a-b). This is consistent with the hypothesis that microorganisms colonizing copper and other toxic metals secrete polymeric materials which chelate metal salts (MARSZALEK, 1979). Compounds such as polyuronic acid found in such secretions in the primary layer will raise the TOC: TN ratio for the entire film. Figure 10 is a micrograph of the colonized Cu-Ni heat exchanger surface showing both rod- and filamentous-type organisms.

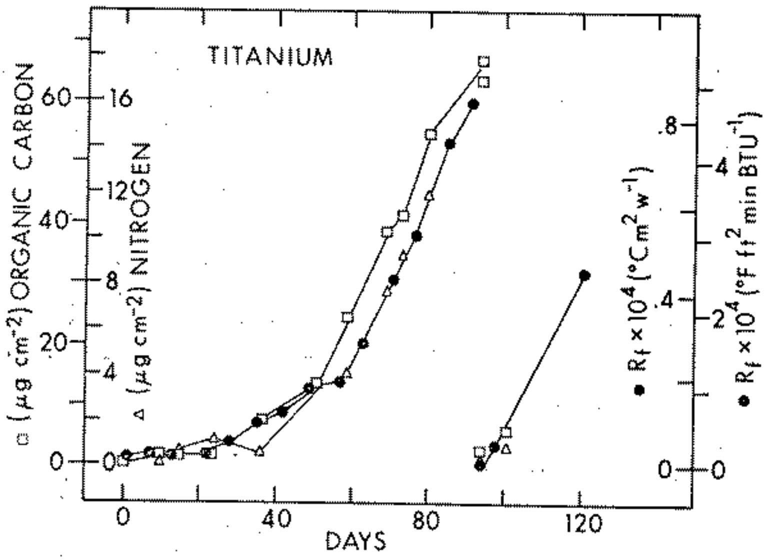


FIG. 2 *a*.—Total organic carbon, total nitrogen, and R_f vs. time for Ti. Curves were generated from model for the Hawaii experiment.

CONCLUSIONS

There were no large changes in the TOC: TN ratios of the fouling films in each of the tube types during the experimental period. The ratios for Ti, SS, and Al were essentially the same (4.2, 4.8 and 4.0 respectively) while that of Cu-Ni was 7.9.

Increases in heat transfer resistance (R_f) for Ti and SS surfaces were related to the TOC and TN in the fouling films. However, the impacts of equivalent films were different on the two surfaces. A film covering the roughened SS surface may trap a film of water and provide a greater insulating effect than that observed on the smooth Ti surface. R_f was proportional to TOC and TN for Al surfaces only after prolonged exposure (> 3 weeks). The formation of a corrosion film appeared to inhibit heat transfer efficiency during the first 3 weeks. Corrosion appeared to be responsible for increased R_f in the Cu-Ni tubes. The Cu-Ni was colonized by microorganisms, but

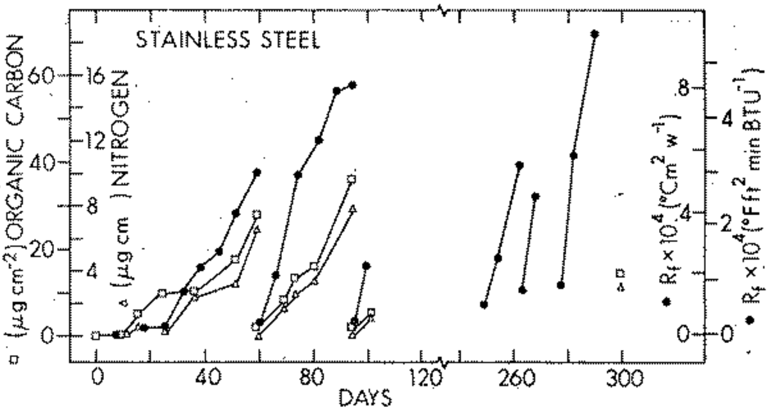


FIG. 2 *b*.—Total organic carbon, total nitrogne, and R_f vs. time for SS. Curves were generated from model for the Hawaii experiment.

their contribution to total dry film weight was small. The large film weights on all tubes, including the corrosion-resistant Ti and SS, suggested that the fouling films contain substantial amounts of inorganics that may effect R_f.

Cleaning with a M.A.N. brush removes most, but not all of the biomass in the fouling films. The first and second cleanings of the Al tubes reduced R_f to zero. Subsequent cleaning after 100 days appeared less effective. The rate of fouling increased after cleaning.

BIOFOULING MODEL

A model is proposed for the kinetics of biofouling on corrosion-resistant tubes such as Ti and SS maintained under the OTEC conditions described.

Sea water flowed through tubes (i.d. 2.5 cm) at approximately 2 meters per second. Heat transfer resistance (R_f) was measured periodically and samples of the pipe were removed for analysis of the biofouling layer. Biofouling was assumed to be the cause of the increase in R_f for the corrosion-resistant metals. The rate of refouling after cleaning on such tubes is also considered in the model. The model is limited to early fouling in open ocean waters in which flow rates and water quality are assumed to remain constant during the experiment.

DESCRIPTION OF THE BIOFOULING MODEL

1. The rate of primary colonization, dC/dt depends on available uncolonized space, A', and the density of colonization per unit of space, a'. Since experimental data for A' and

TABLE 2

TOTAL ORGANIC CARBON TO TOTAL NITROGEN RATIOS IN FILM ON VARIOUS TUBE TYPES

(HI Data)

Tube Type	*TOC/TN Ratio* *
Ti	4.2 ± 0.9
SS	4.8 ± 0.7
Al	4.0 ± 0.8
Cu-Ni	7.9 ± 0.8

* 1. Zero-values substracted for all but Al.
2. Average of 2 values for most times.
3. Values taken 1 day after cleaning or removal.
4. Wildly abberant values deleted.
5. Each ratio based on 12 or more values.

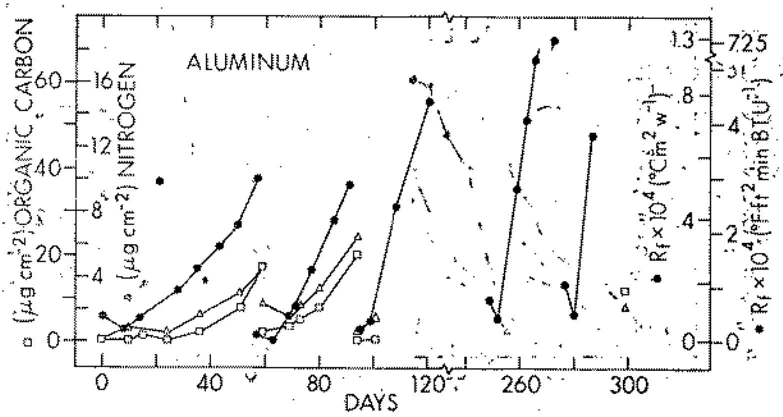


FIG. 2 c.—Total organic carbon, total nitrogen, and R_f vs. time for Al. Curves were generated from model for the Hawaii experiment.

a' are lacking in the current studies only their product, A ($A = A' \cdot a'$), is considered. The rate is also dependent on a variety of physical and chemical factors characteristic of the particular system. These factors are lumped together in a constant, K

$$dC/dt = (A - C)\ K \qquad 1\ a)$$

rearranging:

$$dC/(A - C) = K\ dt \qquad (1\ b)$$

Integrating (1 b) between t = 0 and ∞ [equation form: $dy = dx/(a + bx)$] gives:

$$C = A\ (1\text{-}\exp - Kt) \qquad (2\ a)$$

or

$$C = A - A\ (\exp - Kt) \qquad (2\ b)$$

2. The growth of the primary colonizers (and/or production of metabolic products), S, is proportional to their number, the time, and a growth (or slime-production) constant, K_1. In the simplest form,

$$S = C \cdot K_1 \cdot t \qquad (3)$$

3. Secondary microbial colonization, i.e., biofouling by other organisms, N, depends upon time, S, and an adhesion constant, K_2:

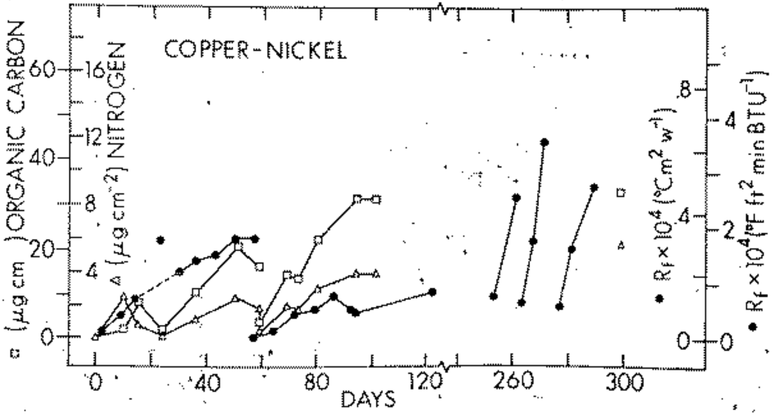
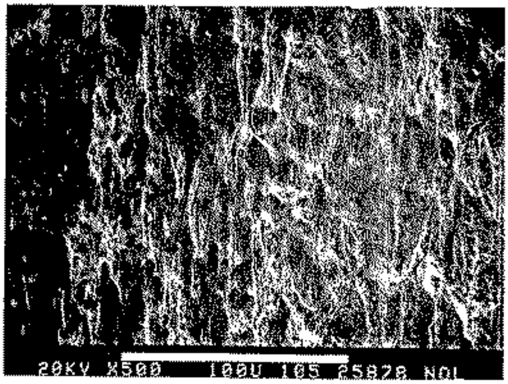
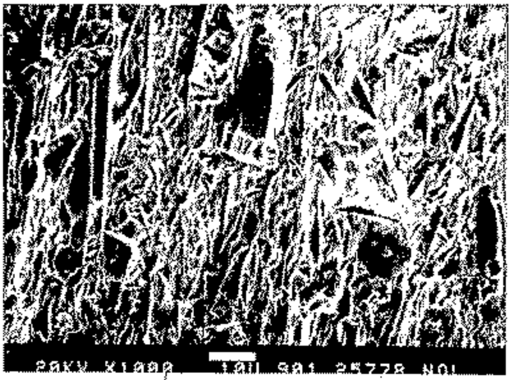


FIG. 2 d.—Total organic carbon, total nitrogen, and R_f vs. time for Cu-Ni. Curves were generated from model for the Hawaii experiment.



a) Zero hour Ti.



b) Zero hour SS.

FIG. 3.—Scanning electron micrographs of tube surfaces before exposure to sea water.

K_2 also includes a concentration factor, i.e., number of cells/volume of water:

$$N = S \cdot K_2 \cdot t \qquad (4)$$

4. Finally, total biomass, B, of the biofouled layer is

$$B = C + S + N \qquad (5)$$

5. Substitution of equations 1, 2, 3, 4, into 5 gives

$$B = A\ [(1 - e^{-Kt})\ (1 + K_1 t + K_1 K_2 t^2)] \qquad (6)$$

It becomes evident that A is also a «scaling factor» dependent on the units used. When $K_2 >>> K_1$, the equation becomes largely dependent on the final term especially when t is not small and when K is small compared to K_1 and K_2.

1. The model ignores the various reactions which occur during the first minutes or hours following initiation of the flow of water. The first event considered in the model is the attachment (colonization) of those bacteria which have very high adhesive affinity for the tube surface. Colonization is random as the organisms come into contact with the surface from the seawater. Their rate of adhesion on the tube, however, depends on many factors:

a. Their numbers per unit volume of water.

b. Their kind (i.e., their degree of «stickiness»).

FIG. 4.—Micrograph for 78-day exposure SS.

c. The flow rate of the water and the hydrodynamic properties of flow.

d. The smoothness of the tube surface.

e. Other factors such as temperature, organic content of the water, etc.

f. The limited area for colonization.

2. The initial colonizers are responsible for making the tube «sticky» for other groups of fouling bacteria. Growth of the primary colonizers, if it occurs, and slime production are assumed to be in direct proportion to cell number and time; nutrient concentration limits growth and metabolic product formation.

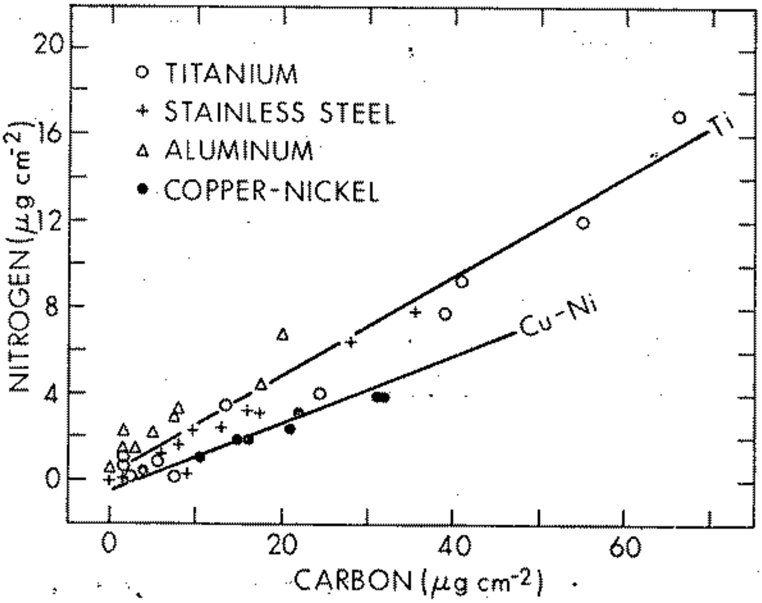


FIG. 5.—Total nitrogen vs. total organic carbon in the fouling films.

3. Other bacteria, secondary colonizers, adhere randomly to the surface at a rate proportional to their numbers and affinities as well as to the amount of growth or slime already adhering to the tube surface. In the time frame considered no limitation of colonizing space is assumed for the secondary colonizers.

4. During the cleaning of the tubes it is

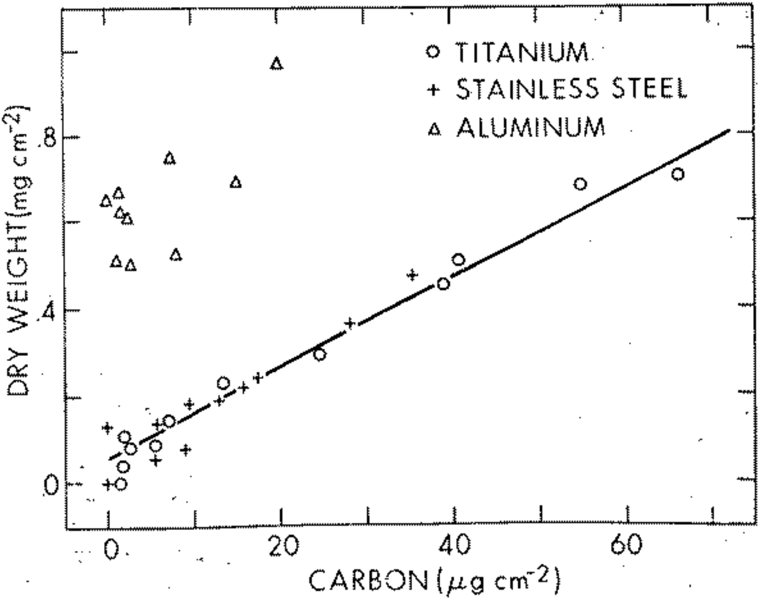


FIG. 6.—Dry film weight vs. total organic carbon in the fouling films.

assumed that the primary colonizers, their progeny and/or their macromolecular products are not removed. In contrast most or all of the secondary colonizers are assumed removed. Recolonization then occurs at a rate dependent on the amounts of adhering materials still on the pipe.

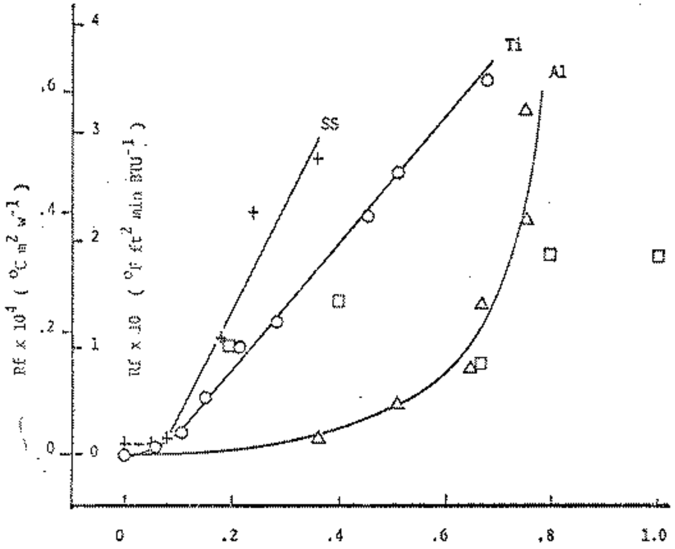


FIG. 7.—R_f vs. dry film weight (Hawaii data).

ANALYSIS OF BIOFOULING MODEL

Figure 9 a shows three superimposed theoretical curves drawn over the R_f, total organic carbon and total nitrogen data from Ti in the HI experiment. The constants used in the model equation are given in Table 3. Since the magnitude and units of the 3 data sets are different, the constant A is scaled to give comparable numerical values for the Ti data. These same values of A are used for the SS data. The same values K and K_1 are used to generate all of the Ti curves. K_2 is chosen to make each curve fit the experimental data. For all Ti curves, K_2 varies little. Figure 11 shows a curve constructed through the data obtained in the Gulf of Mexico. Note from Table 3 that K_2 is only slightly lower than in the HI curves.

A larger value of K for SS (0.06) is required compared to that for Ti (0.01). This may result from the rougher surface of the SS or other factors which permitted the SS surface to be colonized more rapidly than that of Ti. Curves 3 through 10 in Figure 9 b for SS mimic the increase in the fouling parameters after cleaning of the tube. Except for curves 1, 3 and 6 (Fig. 9 b), values of K_2 are relatively constant for each parameter. No explanation is offered for this apparent temporary increase in «secondary colonization» in curves 1, 3 and 6. Similar anomalies were not observed on any other tube or parameter measured.

For both the Ti and SS systems, the «secondary colonization» term is set back to a time value equivalent to the start of the experiment (zero to 3.5 days). This supports the premise made in deriving the model. It further indicates that the model may be used to predict fouling rates after repeated cleaning of metal surfaces. The gradual rise in the starting value of R_f following repeated cleaning can be attributed to the combined C and S terms of

TABLE 3

BIOFOULING MODEL:

CONSTANTS GIVING GOOD-FITTING CURVES THROUGH PLOTS OF THE EXPERIMENTAL DATA FOR FOULING BEFORE AND REFOULING OF TUBES AFTER CLEANING

Site	*Tube Type*	*Measured Parameter*	*Following Cleaning #*	MODEL CONSTANTS * *A*	*K*	*K1*	*K2*	*Day Series Begun*	*K2 Pushed Back to —— Day*	*See Fig. #*	*Curve #*
Gulf Mexico ...	Ti	R_f	0	.00505	.01	.03	5.0	0	—	10	
Hawaii	Ti	R_f	0	.00505	.01	.03	6.5	0	—	9	1
Hawaii	Ti	R_f	1	.00505	.01	.03	6.5	94	0	9	2
Hawaii	Ti	Org. C	0	.06313	.01	.03	7.5	0	—	9	1
Hawaii	Ti	Org. C	1	.06313	.01	.03	6.5	94	0	9	2
Hawaii	Ti	N	0	.01683	.01	.03	6.5	0		9	1
Hawaii	Ti	N	1	.01683	.01	.03	6.0	94	0	9	2
Gulf Mexico ...	SS	R_f	0	.00505	.06	.03	5.5	0	—	10	
Hawaii	SS	R_f	0	.00505	.06	.03	6.0	0		9	1
Hawaii	SS	R_f	1	.00505	.06	.03	11.0	59	1	9	3
Hawaii	SS	R_f	2	.00505	.05	.03	17.0	94	0	9	6
Hawaii	SS	R_f	3	.00505	.06	.03	6.0	249	2	9	8
Hawaii	SS	R_f	4	.00505	.06	.03	7.5	263	3	9	9
Hawaii	SS	R_f	5	.00505	.06	.03	7.0	277	3.5	9	10
Hawaii	SS	Org. C	0	.06313	.06	.03	4.5	0	—	9	2
Hawaii	SS	Org. C	1	.06313	.06	.03	5.5	59	1	9	4
Hawaii	SS	Org. C	2	.06313	.06	.03	4.5	94	0	9	7
Hawaii	SS	N	0	.01683	.06	.03	4.0	0	—	9	2
Hawaii	SS	N	1	.01683	.06	.03	4.5	59	1	9	5
Hawaii	SS	N	2	.01683	.06	.03	4.0	94	0	9	7

* See text for explanation of symbols.

the model: these are small numerically and unaffected by cleaning. They continue to increase with time.

The model curves generated for Ti and SS for GOM data, Figure 11, only fit in the early part of the experiment. It appears that the next stage of fouling, that which limits further rapid increase in R_f, was reached earlier than in the HI experiment. The model does not apply to this stage.

A single value of K_1 was used to generate all curves presented in Figures 9 (a-b) and 11. This value, 0.03, is arbitrary. The magnitude of K_2 is inversely related to K_1. An independent measurement of either «primary colonizers», C, and their products, S, or of «secondary colonizers», N, would permit assigning absolute values to K_1 and K_2.

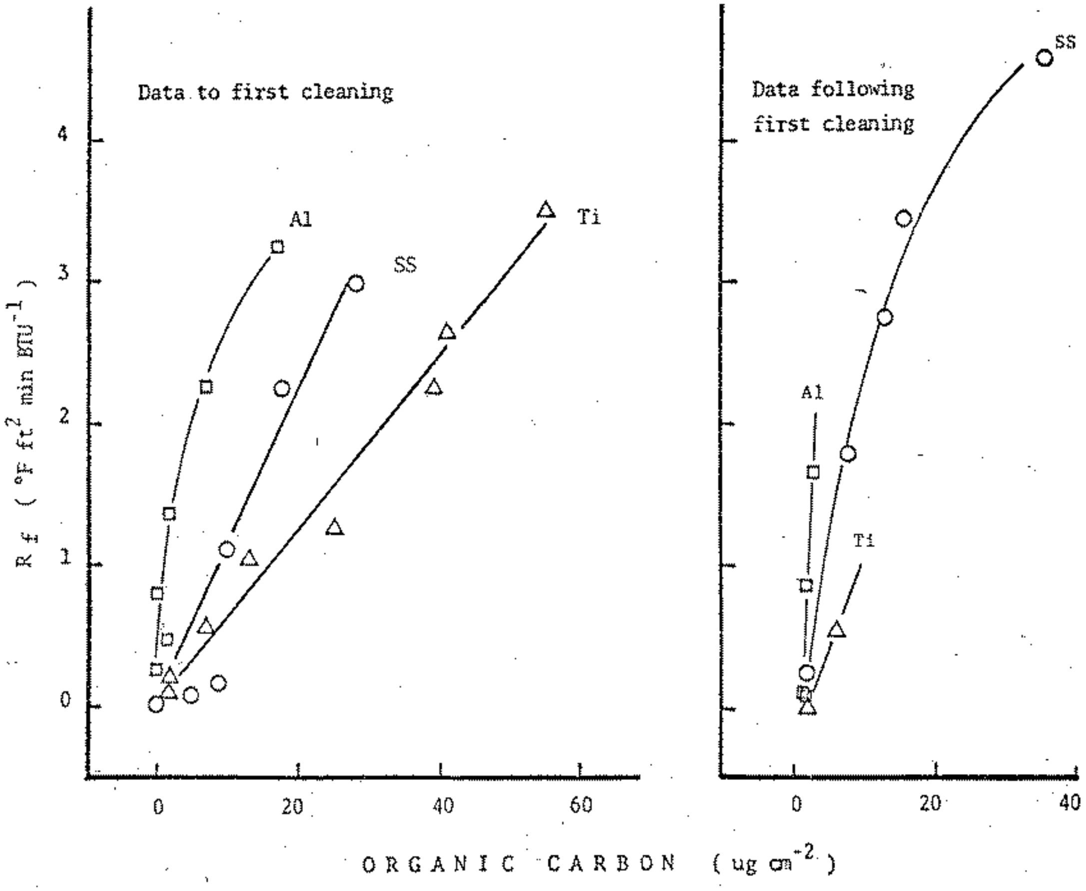


FIG. 8.—R_f vs. total organic carbon (Hawaii data).

The lower values given for K_2 in the organic carbon and nitrogen curves on SS compared to the R_f curves may not be due to differences in the rates of secondary colonization, but to different colonizing densities on Ti and SS surfaces. These should be distinguished in the constant A rather than in K_2.

The precision of the field data makes a more detailed analysis of the model impractical. It is evident that the fouling layer does not form

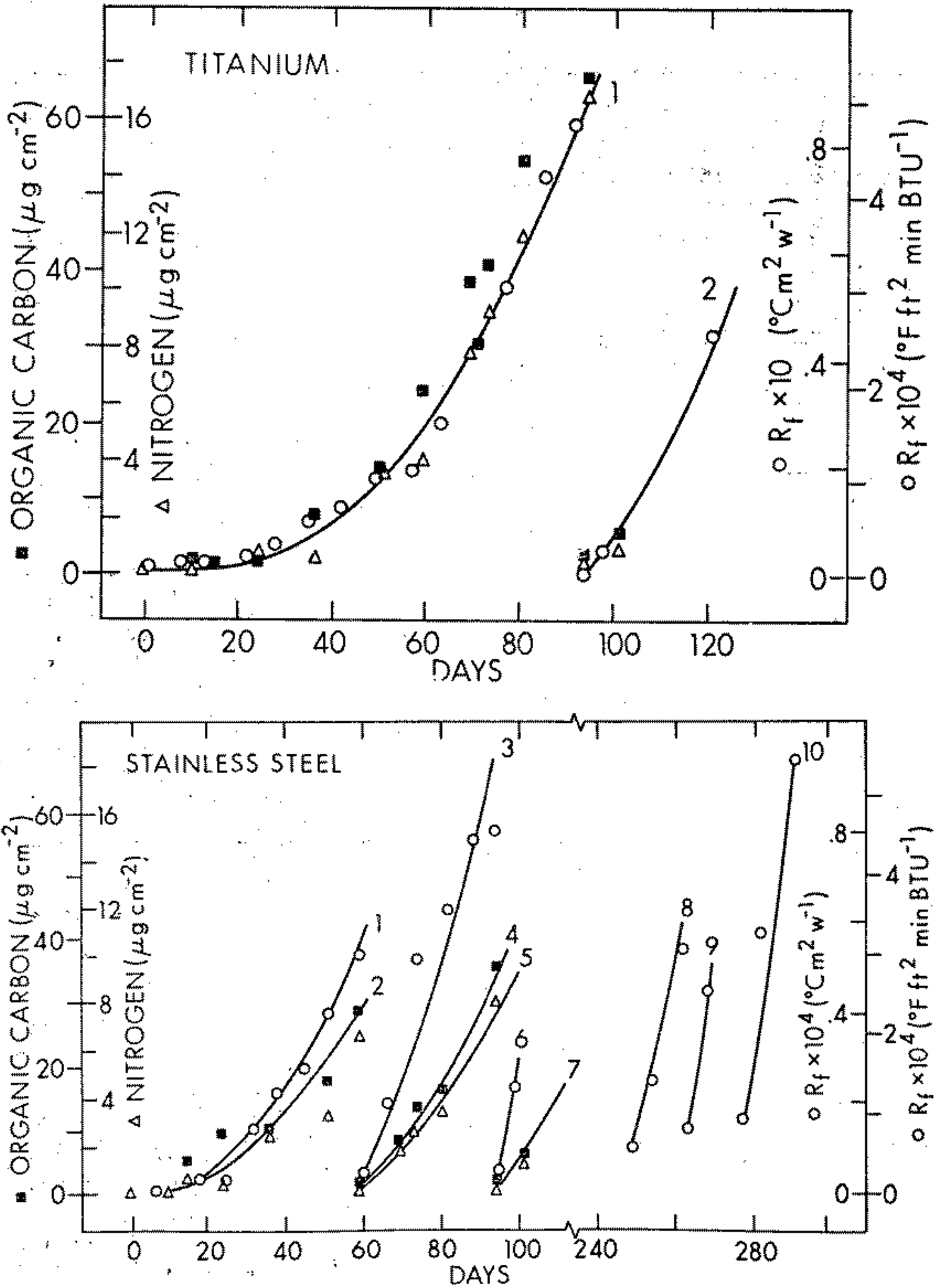


FIG. 9.—Total organic carbon, total nitrogen and R$_f$ vs. exposure time, Hawaii data. The curves were generated from equations of the model.

FIG. 10.—Cu-Ni surface fouled with rod- and filamentous-type microorganisms.

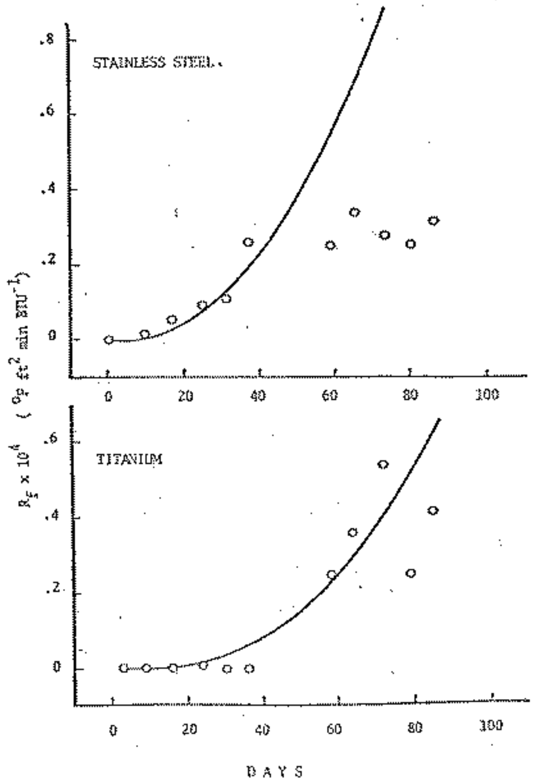


FIG. 11.—R_f vs. time. Smooth curves generated from model for the Gulf of Mexico experiment.

in an expontential manner. This could occur under conditions in which nutrient levels are higher than those found in the present experiment. The model proposed by BRYERS *et al.* (1979), for biofouling was derived for a system exposed to light and in which nutrients were added. The present model does not include a term to limit the increase in the fouling rate.

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A SURVEY OF MARINE BORER ACTIVITY IN HAWAIIAN NEARSHORE WATERS: EFFECTS OF ENVIRONMENTAL CONDITIONS AND EPIFAUNA

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ABSTRACT

Test exposures were conducted at various locations around the island of Oahu, Hawaii, to investigate the relationship of wood boring activity to environmental factors and surface epifaunal fouling. Data were collected from various field sites, exposures in a flow-through sea-water microcosm facility, and drift wood borer communities. All test exposures were unpainted blocks of Douglas fir (10 × × 10 × 20 cm) suspended by ropes and eye-bolts with all sides exposed. Blocks were exposed for periods of three and six months in the field, and for one year in the experimental facility. The epifaunal communities on these blocks were examined by photographic and grid-quadrat sampling methods, and the percent cover of the epifaunal communities and the frequencies of the major taxa were determined. Teredinid borers and *Limnoria* were quantified after extraction from the wood, although subsampling was necessary in some because of extremely high borer numbers.

Wide variation was found in borer activity between the various sites, even those less than 3000 meters apart in the same bay. Densities of teredinid borers ranged from 0 per block to about 6000/block (1 per 0.2 cm^3). *Limnoria* densities ranged from 0 per block to approximately 87 per cm^2 of wood surface. The teredinids *Teredo furcifera, T. bartschi, T. clappi, Lyrodus pedicellatus* and *Bankia bipalmulata* were dominant in embayments, and the more polluted areas, while *L. affinis,* and a few *L. medilobata, T. bartschi* and *T. clappi* were found at the open coast sites. *L. affinis* and *Teredora princessae* were both found in the drift material. The greatest teredinid activity was found at the Makai Range, an open coast site where an epifaunal fouling community never developed on the blocks. The greatest *Limnoria tripunctata* activity occurred at sites int he Hawaii-Kai Marina, even though substantial epifaunal communities did develop here. At locations in Pearl Harbor and Kaneohe Bay, reductions in borer activity were associated with epifaunal communities consisting of compound tunicates and tubicolous polychaetes. Borer activity was less affected by epifaunal communities dominated by serpulid tubeworms and barnacles. Portions of the epifaunal community were lost from some blocks after exfoliation of the wood surface resulting from heavy *Limnoria* damage. The test blocks in the flow-through experimental microcosm facility collected no *Limnoria,* and fewer teredinids than expected even though no epifaunal fouling community developed on these blocks. This likely resulted from low larval availability, and perhaps larval susceptibility to pumping and entrainment damage.

The results of this study show that borer and surface epifaunal populations do interact with each other, and the amount and kind of surface fouling can reduce borer activity, while intense borer activity will cause loss of the

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surface fouling. Even within a harbor, there is great variation in borer activity. In any location a single test site is unlikely to give a representative picture of the maximum borer potential especially if heavy fouling is also present. The importance of studying the interactions between settling borer larvae and the epifaunal species, and the feasibility of flow-through microcosms for the study of wood boring communities are also discussed.

INTRODUCTION

This investigation examines competitive interaction between surface fouling communities and borer communities, particularly the effect of the surface fouling on the borer community, in experimental wood blocks. We specifically investigated whether the amount and kind of surface fouling affected the success of borer populations and whether particular taxa or characteristics of the surface community had more influence than others on the success of the borers. Our primary interest was the demonstration of competition between species which use a particular resource in distinctly different ways, and the determination of whether such indirect competition and interference contributes to overall borer and fouling community structure.

Although most research on competition as a factor in community organization (for review see CONNELL, 1975) has focused on competition between species which have the same uses and requirements for a limited resource, there are many resources which can be used in several different ways. Presumably each use and user of a resource affects the success of the other users to some degree. Usually the interactive and interference effects of multiple utilizations are not specifically investigated although any use which makes a resource less available to any other organisms must contribute to competition and the web of interactions and relationships which are community structure. While in most communities with large numbers of component species the multitude of possible interactions are overwhelming, simple communities exist where these relationships may be examined.

Wood in the ocean is a resource which may support a total community consisting of both surface and internal components. While its solid surface is used as substratum for a community of epifaunal fouling organisms, the bulk of the wood is consumed by a simple community of a few species of boring organisms such as shipworms (Mollusca, Teredinidae), and various wood eating crustaceans such as *Limnoria, Chelura, Tropichelura* and others who support some few commensals, parasites and predators. In the total community the various fouling and boring populations must have more of an obvious interactive effect than in many other multiple utilization situations. The surface foulers require solid substratum as space to settle, attach, and grow, feeding from the surrounding water, while the borers metamorphose on the surface then enter the wood. The bulk of the wood usually provides most if not all of their food. Thus heavy surface fouling would be expected to reduce the settling success of larval borers by physically blocking the substratum, as well as by the ingestion of settling larvae by various plankton-feeding foulers. Even the remnants of a fouling community, i.e. the calcareous tubes, tests, colonies and shells of polychaetes, barnacles, bryozoans and molluscs, may provide a formidable barrier to settling borers. Growth of the fouling organisms could also interfere with established borers by covering teredinid siphon holes, or blocking *Limnoria* tunnels. Conversely, if sufficiently heavy, boring could be expected to reduce the settlement success, interfere with growth, and, perhaps, shorten the life of the fouling organisms. In heavily bored wood, sessile epifauna would suffer direct physical disturbance from surface borers such as *Limnoria* which would dislodge settling larvae, before attachment, disrupt the growth of colonial forms such as bryozoans and compound tunicates or weaken the wood to which the fouling was attached. Even if the surface of the wood were not disrupted by *Limnoria*, loss of attached fouling organisms could also occur by exfoliation of the outer surface layer of the wood after weakening by deeper borers such as teredinids.

Evidence for such indirect competitive interaction between fouling and borer populations is limited and partially contradictory. WEISS (1948) and NAGABHUSHANAM (1960) as well as anecdotal reports cited in NAIR and SARASWATHY (1971) suggest that heavy fouling of the wood surface would reduce penetration by shipworms. WATSON *et al.* (1936), however, found that the presence of fouling may enhance borer success. NAIR (1962) found that unless the fouling was of a «mat-forming type» consisting of tubicolous polychaetes and amphipods, there was little effect on the number of teredinids found in the bulk of the wood. FUNG and MORTON (1976) suggest that heavy *Limnoria* activity can similarly interfere. None of these studies were as detailed as the numerous studies which have investigated direct competition between epifaunal foulers (for example, CONNELL, 1961; OSMAN, 1977; SUTHERLAND, 1978).

Several prior studies have investigated fouling and borer communities in the Hawaiian islands, but none have considered the interaction between the fouling community and the success of the borers. Most have been descriptive, or concerned with the practical aspects of marine fouling and borer activities. Earlier fouling studies performed in Kaneohe Bay, and Pearl Harbor, Oahu, were detailed in EDMONDSON and INGRAM (1939) and EDMONDSON (1944 *a*). Recent studies are reported in *Evans et al.* (1972), LONG (1972), MCCAIN (1975), and RASTETTER and COOKE (1979). The occurrence, taxonomy, and aspects of the zoogeography of the various teredinids found in Hawaii are discussed in EDMONDSON (1942, 1946 *a*, 1946 *b*, 1962). Ecological aspects of Hawaiian teredinids, and investigations of the resistance of various woods and preservative preparations in Hawaiian waters are reported in EDMONDSON (1944 *b*, 1945, 1947, 1953, 1955). LONG (1972) also briefly discusses borer activity off Oahu.

Preliminary investigations showed a wide range of borer success at different locations and suggested that borer infestation was inversely related to surface fouling. This particular report is part of a more extensive survey of nearshore fouling and borer communities around the island of Oahu, Hawaii, which will be published separately.

MATERIALS AND METHODS

The experimental wood blocks used in this study were 10 × 10 × 20 cm pieces of untreated, unpainted Douglas fir *(Pseudotsuga menziesii)*. The blocks were mounted to minimize physical contact with the surrounding surfaces and fouling communities, and yet allow maximum unimpeded access to all surfaces of the wood. Each block was suspended one meter below tidal datum (MLLW) by ropes from a surface support. The blocks were hung long axis vertical, with the suspending rope tied to an iron eye-bolt on the top face. Several links of iron chain attached to an eyebolt on the bottom face kept the block submerged.

Eleven stations were selected around the island of Oahu based on preliminary experiments. Three were in Pearl Harbor; four were in Kaneohe Bay, one was at the Makai Range Pier and three were in Hawaii Kai, a former Hawaiian fishpond now the site of a small boat marina. Blocks were also exposed at the Ulupau Marine Microcosm Facility. Samples from fresh driftwood were also examined. The locations of these field sites are shown on figure 1. Station 1 was located at Merry Point between piers M2 and M3 in southeast loch, Pearl Harbor (21° 21' 20" N, 157° 56' 47" W) in a location subject to various pollutant stresses (organic enrichment, oil, heavy metal) from nearby activities and ship traffic. Station 2 was located at channel marker # 16 on the east side of the Pearl Harbor entrance channel (21° 20' 10" N, 157° 58' 15" W) in a location with strong water motion, light to moderate organic enrichment and chronic oil exposure. Station 3 was located at Alpha Docks between piers A3 and A4 near the entrance to Pearl Harbor (21° 19' 57.5" N, 157° 58' 10" W) in a location exposed to moderate pollution as well as oceanic water. Station 4 was located at the end of the T-pier at the Naval Ocean Systems Center (21° 27' 13" N, 157° 46' 50" W) facing the outer (1500 m wide) reef flat of Kaneohe Bay. Station 5 was located at the west side of Coconut (Moku o Loe) Island (21° 26' 08" North, 157° 47' 35" W) in the sheltered channel between the island and the shore of Kaneohe Bay. Both Station 4 and Station 5 were considered relatively unpolluted. Station 6 was located at the end of the Kokokahi pier on the south shore of Kaneohe Bay (21° 25' 05" N, 157° 46' 54" W) in a location exposed to sewage pollution from a municipal outfall which was in operation during this study. Station 7 was located at the end of the Fuel Pier, Kaneohe Marine Corps Air Station (21° 26' 26.5" North, 157° 46' 05" W) in a location exposed to some ship traffic and some sewage pollution from the base outfall. Station 8 was located near the end of the Makai Range pier (21° 19' 22" N, 157° 40' 18" W) in a location exposed directly to oceanic water across a narrow (100 m) reef flat. Station 9 was located at a private pier at the inner end of Hawaii Kai (21° 17' 47.4" N, 157° 41' 52.2" W). Station 10 was located at the end of the Hawaii Kai Marina pier (21° 16' 56" N, 157° 42' 31.2" West). Station 11 was located at a private pier in the western end of Hawaii Kai (21° 17' 22.9" North, 157° 42' 49.2" W). All Hawaii Kai stations were exposed to only small boat traffic, light oil and organic enrichment and terriginous turbidity which was greater at the inner stations, 9 and 11.

Surface salinities and temperatures at these stations varied between 30 ‰ and 35 ‰ and between 23° C and 28° C (BATHEN, 1968; GROVHOUG and EVANS, unpubl. data). The lower salinities were encountered only after winter rains and generally at the one meter depth of the test blocks, only small reductions in salinity occured. The stations were basically similar in hydrographic conditions, although variations were present in amount of organic enrichment, oil pollution, and water motion.

This range of conditions produced a qualitative and quantitative diversity in the fouling communities at the different sites, a central requirement of this study. We considered the borer components of the community subsisting within the wood less likely to vary between locations on the basis of external conditions such as water motion, illumination, turbidity, etc. All of these stations have been previously used in fouling community and bioindicator evaluation studies (EVANS, GROVHOUG, unpublished data).

At the Ulupau facility, two blocks were suspended in .5 m depth in an unshaded 500 l tank receiving 5-5 l/min of unfiltered sea water drawn from the front of a natural reef flat. A full description of this facility and its capabilities may be found in HENDERSON, SMITH and EVANS (1976). This experiment was designed to test the capability of this facility to collect and maintain teredinid borers under conditions were a wide variety of environmental factors (nutrient load, water motion, light) could be manipulated.

Preliminary exposures at the field sites were for six months, which were later reduced to three months which was sufficient for the development of the fouling and borer communities at these stations. The test blocks were exposed in two six-month and four three-month series over the course of two years. Series A ran from 11-June-1975 to 21-Dec.-1975, and series B ran from 21-Dec.-1975 to 11-June/3-July-1976. Series I ran from 27-July-1976 to 27-Sept.-1976. Series II ran from 27-Sept.-1976 to 27/28-Dec.-1976. Series III ran from 27/28-Dec.-1976 to 29-March-1977. Series IV ran from 29-March-1977 to 28-July-1977. Blocks at the Ulupau facility were exposed from 1-May-1978 to 3-April-1979.

At the end of each exposure period the blocks were retrieved, transported alive to the laboratory and photographed to provide a permanent record of the surface fouling and aid in identification of species whose live color is an important diagnostic feature. The blocks were then preserved in 10 % formalin and then stored in 70 % isopropyl alcohol. The wash containing the vagile organisms was preserved and examined for surface borers such as *Limnoria* which had been washed from their tunnels. Sessile fouling species were identified and quantified at the lowest taxonomic level possible.

The surface community on each lateral face of the block was quantified using a transparent grid and the frequency count method used in previous studies (RASTETTER and COOKE, 1979). On each lateral face, the presence of one or more specimens or portions of each identified taxon was recorded from 78 regularly spaced quadrat squares of dimensions 0.5 cm by 0.5 cm from a grid of 800 squares. The frequency of *Limnoria* tunnels (grooves) was also recorded in this manner (after removal of fouling if it was obscuring the surface).

A subsample of approximately 10 % of each face had been found (RASTETTER and COOKE, 1979; GROVHOUG and RASTETTER, unpublished data) to be an adequate sample for similar fouling communities. These counts were then expressed as percent frequencies. The total percent surface coverage by the complete fouling community on each face was recorded on the basis of every square in the 800 square grid. Percent surface cover thus included other components such as sponges, solitary tunicates, amphipod tubes, coralline algae, and other biota which were not among the commonest taxa. Each square with only filamentous algae, a light detrital film, or visible wood was considered uncovered. For the block as a whole, values for the four lateral faces were averaged to give a block mean percent frequency or mean percent cover. The top and bottom faces were not included as the fouling on these surfaces was often damaged by the supporting ropes or weights. Surface fouling was removed, dried to constant weight at 100° C, and weighed. After the blocks were X-rayed to locate the borers these were removed by carefully splitting the wood with chisels and small picks. If feasible, removal continued until all fragments of the block had intact unbored surfaces, so all teredinids and *Limnoria* were sampled from most blocks. In the cases of very high teredinid and *Limnoria* density, subsampling was necessary. Identification of teredinid borers followed TURNER (1966). To evaluate the temporal pattern of borer settlement a size frequency distribution was obtained using measurements made with an ocular micrometer of valve and body dimensions on specimens of *Lyrodus affinis*, the most numerous teredinid. The reproductive success of the teredinid borers was evaluated by recording the presence of brooding embryos or veligers in the adult mantles.

Although the frequency counts were made at the lowest taxonomic level for each of approximately fifty identifiable fouling taxa, related taxa were combined for the purposes of analysis. Related taxa within defined larger categories were considered to have similar biological effects. Use of the higher categories greatly reduced the number of independent variables in the analysis, and the variability in the data. Six such categories of surface foulers were chosen to represent the most abundant taxa encountered on the surface of these blocks. «*Balanus* spp.» included *B. eburneus, B. reticulatus,* and *B. trigonus,* but did not include unidentified specimens smaller than 0.5 mm or cyprids. «*Hydroides* spp.» included *H. elegans* and *H. lunulifera.* «Compound tunicates» included *Diplosoma macdonaldi, Didemnum candidum, D. edmondsoni, Trididemnum savignyi, Botrylloides* sp., *Symplegma* sp., and *Polyclinum* sp. «Tubicolous polychaetes» included *Demonax leucaspis, Branchiomma cingulata,* and several unidentified terebellids and chaetopterids. «Bryozoans» included the encrusting forms *Holoporella aperta, H. brunea, Holoporella* sp., *Schizoporella errata,* and *Watersipora edmondsoni.* «Hydroids» included *Clytia* spp., *Bougainvillia* sp., *Obelia dichotoma,* and unidentified clavids, corynids, and a sertularid.

Since the data were collected by individual taxa, and not by these categories, the mean percent frequency per block for each of these composite categories was calculated from the frequencies of the individual taxa. The most probable frequency of a category was used as this value appeared to best estimate the true importance of any category in the fouling community. This value is based on the likelihood of encountering any component of that category alone in any grid square, with another component of the same category, with two others, and so forth.

This composite percent frequency (F_c) was computed using the formula:

$$F_c = \Sigma_i^n P_i - \Sigma_{i<j} P_i P_j + \Sigma_{i<j<k} P_i P_j P_k$$

where P_i = the percent frequency (mean per block) of the i^th^ taxa (and so forth) of any category. The formula was not extended to include any combination of four taxa as the change in F_c produced was insignificant with these data (0.0008 in the largest case). This F_c for each of the six fouling categories was used in the analysis, although the use of the sum of the frequencies of the component taxa gave generally similar results. All percent frequencies and percent cover values were transformed using the arcsine transformation for proportions ($y = \sin^{-1} x^{\cdot 5}$) (SNEDECOR and COCHRAN, 1967, p. 327), and all statistical tests were performed on these transformed data, except where noted.

Multiple stepwise regression of the number of teredinids per block in both series separately against the factors of the surface community was performed to evaluate such interactions.

TAB

NUMBER OF SPECIMENS OF EACH SPECIES OF BORER RECOVERED

	STATION 1			STATION 2				STATION 3				STAT	
Series	*I*	*II*	*III*	*I*	*II*	*III*	*IV*	*I*	*II*	*III*	*IV*	*I*	*II*
TAXA													
Bankia bipalmulata				0	0	1	0						
Lyrodus affinis								2	2	0	3	1	10
L. pedicellatus	0	2	5	0	0	2	1	0	1	0	1	0	0
L. medilobata												0	0
Teredo bartschi	0	2	0					0	1	0	0		
T. clappi													
T. furcifera	2	13	17	0	0	0	2	1	4	1	1	2	1
All Teredinids	2	17	22	0	0	3	3	3	8	1	5	3	11
# *Limnoria*	0	0	0	0	0	2	0	0	1	0	0	0	0

* Lost blocks omitted.

The first regression considered all 28 available samples of the three-months series, while the second considered only stations in Pearl Harbor and Kaneohe Bay (excluding one sample with an extreme deviation). No correlations or regressions were performed using *L. tripunctata* from the three-month series as the number of data points were insufficient. Similar regressions were performed for teredinids and additionally for *L. tripunctata* from the six-months series.

RESULTS

Four blocks, Station 2, series B, and Station 3, series A, and both series from Station 4 were lost during exposure leaving 18 out of the original 22. Two blocks, Station 1, series IV, and Station 7, series II, were lost during exposure, and two blocks from Station 6, series I and III, were retreived, but not included in the statistical analysis as their surfaces were damaged in the field. Thus, complete data were available for 28 of the original 32 blocks set out in the three-months series which was analysed more extensively than the six-months series.

Seven species of teredinids, one specimen of a copepod commensal with teredinids, one species of *Limnoria* and one isopod species commensal with *Limnoria* were recovered from the blocks in this study. No specimens of the amphipod *Tropichelura* previously reported from Hawaii, and no other commensals or parasites (EDMONDSON, 1945) were found in these samples. Although the same species were encountered at different sites, there was a wide range in their abundances. Station 8 had the greatest number of borers, both in number of species, six during series II, and in numbers of individuals. *Teredo furcifera* von Martens, 1894, and *Lyrodus pedicellatus* (Quatrefages, 1849) were collected at all eight stations, and were the most ubiquitous species; *L. affinis* (Deshayes, 1863), collected at five stations was the most numerous and was extremely abundant at Station 8. *T. bartschi* Clapp, 1923, and *T. clappi* Bartsch, 1923, were collected infrequently at several stations, while *Bankia bi-*

LE 1

AT EACH STATION DURING THE FOUR EXPOSURE PERIODS

ION 4		STATION 5				STATION 6				STATION 7			STATION 8			
III	*IV*	*I*	*II*	*III*	*IV*	*I*	*II*	*III*	*IV*	*I*	*III*	*IV*	*I*	*II*	*III*	*IV*
3	4	0	1	0	1	0	0	1	0				59	100	59	189
1	2	6	13	8	2	8	4	4	0	0	3	0	0	1	0	1
0	1												0	0	1	0
						1	0	0	0				0	1	0	0
										1	0	0	1	1	0	0
1	0	5	9	10	8	19	0	2	2	0	0	5	0	2	0	1
5	7	11	23	18	11	28	4	7	2	1	3	5	60	105	50	191
0	0	0	0	0	2	0	0	0	0	0	0	0	50	7	1,258	3

palmulata (Lamarck, 1801) was collected only once, and *L. medilobata* (Edmondson, 1942) only twice. The number of individuals of each species collected at each series at the eight stations of the three-month series is shown in Table 1.

Limnoria tripunctata Menzies, 1951, was the only boring crustacean collected. It was abundant at Station 8, an open coast station, as well as at the Hawaii Kai stations, located in a long shallow embayment. As for commensals and parasites, the commensal asellote isopod *Caecijaera horvathi* Menzies, 1951 (COOKE, 1977), was collected from the tunnels of *L. tripunctata* only at Station 8, and one ovigerous female specimen of *Teredicola typicus* C. B. Wilson, 1942, was recovered from a *L. affinis* at Station 3, series IV.

The fouling communities included 57 species (or higher taxonomic category units of sessile organisms), the major ones having been listed above. A complete description of the fouling communities including the vagile species will be published elsewhere. Fouling of the wood blocks was basically similar to that reported for fouling panels at these stations (GROVHOUG and RASTETTER, this volume). The mean (per block) percent frequencies (F_c) of the fouling categories used in the analysis are listed in Table 2. Since Station 8 was quite different from the other stations in the composition of its surface fouling, the percent frequencies for species dominant at that station are listed at the bottom of Table 2.

Table 3 shows the fouling composition and boring intensity at the stations used in the six-months series. Table 4 shows similar data for the Ulupau blocks and a representative piece of driftwood.

The major features of the surface fouling at each station used in both the three and six-months exposures are discussed below. The data from Hawaii Kai, and the Ulupau exposures are discussed separately. Station 1, the innermost station in Pearl Harbor, was completely dominated by the serpulid polychaete, *Hydroides elegans,* which was primarily responsible for the very high dry weights recorded at this station. At this station the calcareous tubes of this species assumed an erect growth

TAB

SURFACE FOULING: % F_c OF FOULING CATE

	STATION 1			STATION 2				STATION 3				STAT	
Series	I	II	III	I	II	III	IV	I	II	III	IV	I	II
TAXA													
Balanus spp. (F_c), %	0	0	0	12	0	63	0	17	45	6	0	56	50
Bryozoans (F_c), %	0	0	0	0	1	10	0	17	16	0	0	10	24
Compound tunicates (F_c), %	1	0	0	58	65	76	39	58	39	62	19	68	44
Hydroides spp. (F_c), %	100	85	87	24	39	55	78	65	81	51	99	0	0
Hydroids (F_c), %	0	0	0	2	6	1	1	0	0	4	1	6	9
Tubicolous polychaetes (F_c), %	0	0	0	59	48	10	39	58	39	62	19	7	1
Surface cover (%)	99	100	100	100	100	99.7	97.5	99.6	99.6	98.9	100	98.5	96.2
Dry weight (grams)	717.4	903.7	617.2	525.8	204	256.2	212.6	289.7	209.1	256.3	279.4	334	234.5
# Teredinids	2	17	22	0	0	3	3	3	8	1	5	3	11
L. tripunctata tunnels (F_c), %	7	0	2.9	0	0	0	0	0	0	0	0	0	0
COMPONENTS DOMINANT													
Filamentous algae (F_c), %	0	0	0	0	0	0	0	0	0	0	0	27	64
Coraline algae (F_c), %	0	0	0	0	0	0	0	0	0	0	0	0	0
Tubinella funalis (F_c), %	0	0	0	0	0	0	0	0	0	0	0	0	0

Number of teredinids (all species) and F_c of *L. tripunctata* tunnels listed also.

form, extending 5 cm-7 cm normal to the surface, presumably because of the intense crowding. The only other prominent member of the fouling community at this station was the solitary tunicate, *Ciona intestinalis,* rare at other locations in this study. *Limnoria* tunnels were present on some blocks at Station 1, but no specimens of *L. tripunctata* itself were recovered from the washings or the blocks.

Stations 2 and 3 in outer Pearl Harbor were basically similar in appearence and composition, as they were both dominated by tubicolous polychaetes *(Demonax leucaspis* and *Branchiomma cingulata)* and by compound tunicates. *Hydroides elegans* and *H. lunulifera* were present at these stations but never as erect masses of tubes as at Station 1. Lesser and variable amounts of Bryozoans and *Bala-*

LE 2

GORIES, % SURFACE COVER, DRY WEIGHT

TION 4		STATION 5				STATION 6			STATION 7			STATION 8			
III	*IV*	*I*	*II*	*III*	*IV*	*I*	*II*	*IV*	*I*	*II*	*IV*	*I*	*II*	*III*	*IV*
43	56	51	60	8	0	16	36	1	16	51	3	0	0	0	0
16	1	24	37	37	61	2	2	2	19	2	34	0	0	0	0
21	10	29	63	20	32	72	69	45	35	42	14	0	0	0	0
3	0	3	3	27	12	1	2	1	3	3	3	0	0	0	0
17	23	0	6	4	19	1	2	1	24	1	37	3	1	1	1
1	1	1	9	10	4	5	0	0	4	3	3	0	0	0	0
82.9	64	81.8	98.3	73.2	87	97.6	83.3	47	83.4	72	47	1	7	20	1
198.6	115.8	102.8	197.7	15.3	23.5	66	96.1	5.8	51.4	146.5	5.2	0.7	1.7	1.0	1.1
5	6	11	23	18	11	28	4	2	1	3	5	60	105	60	191
1	0	6	0	0	0	0	0	0	0	0	0	5.8	5.1	75	38
ONLY AT STATION 8															
74	89	0	0	22	0	0	0	0	0	0	0	40	47	33	3
0	0	0	0	0	0	0	0	0	0	0	0	1	7	18	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	26

nus spp. were also encountered at these stations.

The stations in Kaneohe Bay were usually marked by a lighter development of the fouling community. Station 4 in outer Kaneohe Bay was the only station which had consistently high dominance by *Balanus* spp. Bryozoans and compound tunicates were also important at this station while, in contrast to the Pearl Harbor stations, *Hydroides* spp., and the tubicolous polychaetes were not. Station 4 also had a mean percent frequency of 56 % for filamentous algae, predominantly *Polysiphonia* spp. (Station 8 was the only other station with appreciable algal cover.)

Station 5 at Coconut Island was marked by a wide variation in the development of the fouling community which was heaviest dur-

TAB

SURFACE FOULING: % F_c OF FOULING CATEGORIES,

	STATION 1		STATION 2	STATION 3	STATION 5		STATION 6	
Series	*A*	*B*	*A*	*B*	*A*	*B*	*A*	*B*
TAXA								
Balanus spp. (F_c)	5	1	5	2	29	18	10	26
Bryozoans (F_c)	0	2	0	1	45	0	58	5
Tunicates (F_c)	0	0	0	7	14	42	22	64
Hydroides spp. (F_c) ...	90	85	80	53	0	3	2	1
Hydroids (F_c)	0	0	1	0	0	2	1	2
Polychaetes (F_c)	0	0	12	26	0	0	0	0
Surface cover (%)	100	100	100	100	86	76	45	81
Dry weight (grams) ...	202	1,158	85	289	145	129	37	68
# Teredinids	1	3	23	47	168	16	932	44
# *Limnoria*	0	0	0	0	0	0	1,466	356
Limnoria tunnels (F_c) ...	1	6	0	0	0	0	43	7

Number of terdinids (all species), *L. tripunctata* (# and F_c) listed also.

* Surface area reduced to 552 cm^2 by exfoliation.

** Surface area reduced to 546 cm^2.

ing series I and II, and was considerably lighter during series III and IV. *Balanus* spp. Bryozoans, compound and solitary tunicates and sponges contributed in varying degrees to the structure of the community during different series.

Stations 6, inner Kaneohe Bay, was generally lightly fouled and was usually dominated by compound tunicates, with only one other component, *Balanus* spp. becoming significantly abundant during series II. Settlement of far fewer than normal *Balanus* spp. resulted in very light fouling biomass during series IV at this station.

Station 7 at the KMCAS Fuel Pier was also variable in fouling composition and dominance during the different series. Series IV at this station was also marked by a reduction in *Balanus* spp., and also by an increase in Bryozoans. Station 7 was also notable for the high abundance of hydroids, primarily *Obelia dichotoma*, during series IV. Six-months exposures had good coverage of compound tunicates and sponges.

Station 8, Makai Range, was unique among all the stations and consistently lacked any typical filter-feeding fouling community. This absence was likely a result of the low nutrient conditions (and hence sparse plankton) in the surrounding waters, as well as the activities of grazing herbivorous fishes whose feeding scars were observed on the sand and detritus film on the block surface. This was the only station where coralline algae (as very thin crusts, less than 0.5 mm thick) was found. The coralline algae was often penetrated by *L. affinis* siphon holes, and *Limnoria* tunnels and ventilation holes. A sessile foraminiferan,

LE 3

% SURFACE COVER, WEIGHT FOR SIX MONTHS SERIES

STATION 7		STATION 8		STATION 9		STATION 10		STATION 11	
A	*B*	*A*	*B*	*A*	*B* *	*A*	*B*	*A*	*B* **
5	79	0	0	83	7	6	15	0	0
65	0	0	0	0	0	16	6	6	26
23	78	0	0	0	10	3	9	0	6
1	7	0	0	57	17	13	8	34	5
2	5	2	0	18	0	4	3	19	2
1	1	0	0	55	15	33	38	18	11
83	99	2	0	98	22	89	51	22	18
49	445	2	2	689	94	42	18	43	14
35	1	1,281	6,269	3	0	2	0	6	116
926	24	4,834	3,132	0	47,962	34.504	23.398	30,286	32,125
7	3	55	44	10	80	65	63	87	84

Tubinella funalis Brady, 1884 (COOKE, 1978), was also found only at this station.

The graph of number of teredinids versus percent surface cover for the three-months series is shown in figure 2. However, the teredinid number values were non-normal (significant right skew resulting from the high values at Station 8). Therefore these correlations were also tested using the non-parametric Spearman rank correlation for the untransformed values of percent surface cover, F_c of compound tunicates, and number of teredinids. For compound tunicates the Spearman rank correlation value (r_s) SNEDECOR and COCHRAN (1967, p. 194) was significant at the .01 level $r_s = -.534^{**}$ ($t_{s.01} = .470$), and for the surface cover the test was significant at the .05 level, and nearly significant the .01 level $r_s = -.455^{*}$ ($t_{s.05} = .367$).

Multiple stepwise linear regressions of the number of teredinids against variables of the surface community (arcsine transformed) are presented in Table 5 for three cases. Case I included all stations in the three-months series, while the second case included only Pearl Harbor and Kaneohe Bay stations (less Station 5, series II) excluding Station 8, Makai Range, because Station 8 values introduced significant non-normality, and significantly increased heteroscedasticity in most parameters. Case III considered stations in the six-months series excluding the Hawaii Kai stations, as discussed later. The appropriateness of linear regression to such non-normal data could be questioned, although the regression was highly significant ($p < .001$). The second regression excluding these extreme values from Station 8 also served to evaluate the interactions of sur-

TABLE 4

SURFACE FOULING: % OF FOULING CATEGORIES, % SURFACE COVER, ETC., FOR ULUPAU AND DRIFT MATERIAL

	Ulupau #1	*Ulupau #2*	*Drift item* *
Filamentous algae (F_c)	100	100	0
Coralline algae (F_c)	6	20	0
Spirobinae (F_c)	1	3	0
Lepas spp. (#)	0	0	610
Surface cover (%)	1	1.5	30
L. affinis (#)	134	68	61
L. pedicellatus	1	1	0
T. princessae	0	0	8
Limnoria tripunctata	0	0	0
Dry weight (grams)	2.9	2.8	N.A.

* Drift wood of unknown origin, approximate volume 1,650 cm^3.

face fouling and borer abundance within the more commonly encountered ranges of fouling. The values from Pearl Harbor and Kaneohe Bay samples satisfactorily met the assumptions required of regression analysis. One sample (Station 5, series II) (fig. 3) had 23 teredinid borers and this value seemed extremely divergent. The test of this value against a regression excluding this sample (SNEDECOR and COCHRAN, 1967, p. 157) indicated that it was indeed significantly different from the regression (p = .023) and after reexamination of the data from this station it was discarded from the regression. This sample was characterized by a high frequency of *Balanus* spp., including many large individuals which had apparently settled early in the exposure period, and numerous colonies of didemnid tunicates growing around and over the *Balanus*. These tunicates apparently settled later during the exposure while the teredinids settled earlier when tunicate and overall cover were much lower.

In the first case the surface cover, as expected, explained the majority of the variance, while in the second case, the majority of the variance was accounted for by the contribution of compound tunicates (Table 5). The graph of number of teredinids versus compound tunicates for the three-months series is presented in figure 3. As can be seen by Table 5, most fo the parameters and taxa of the surface fouling did not contribute any further reduction of the variance in this regression. The dry weight of the surface fouling, the percent surface cover, and the frequencies of *Balanus* spp., *Hydroides* spp. and tubicolous polychaetes did not contribute any significant reduction in the variance explained by regression. Frequency of tubicolous polychaetes and percent surface cover were significantly positively correlated with the frequency of compound tunicates, and as such, would not produce any greater reduction in the variance. Two taxa of the surface community contributed in a minor way to the regression, bryozoans, and hydroids. These were considerably less important than compound tunicates; the bryozoan coverage was actually positively correlated in a minor way and may represent similar settlements histories.

As can be seen by Case III, the situation

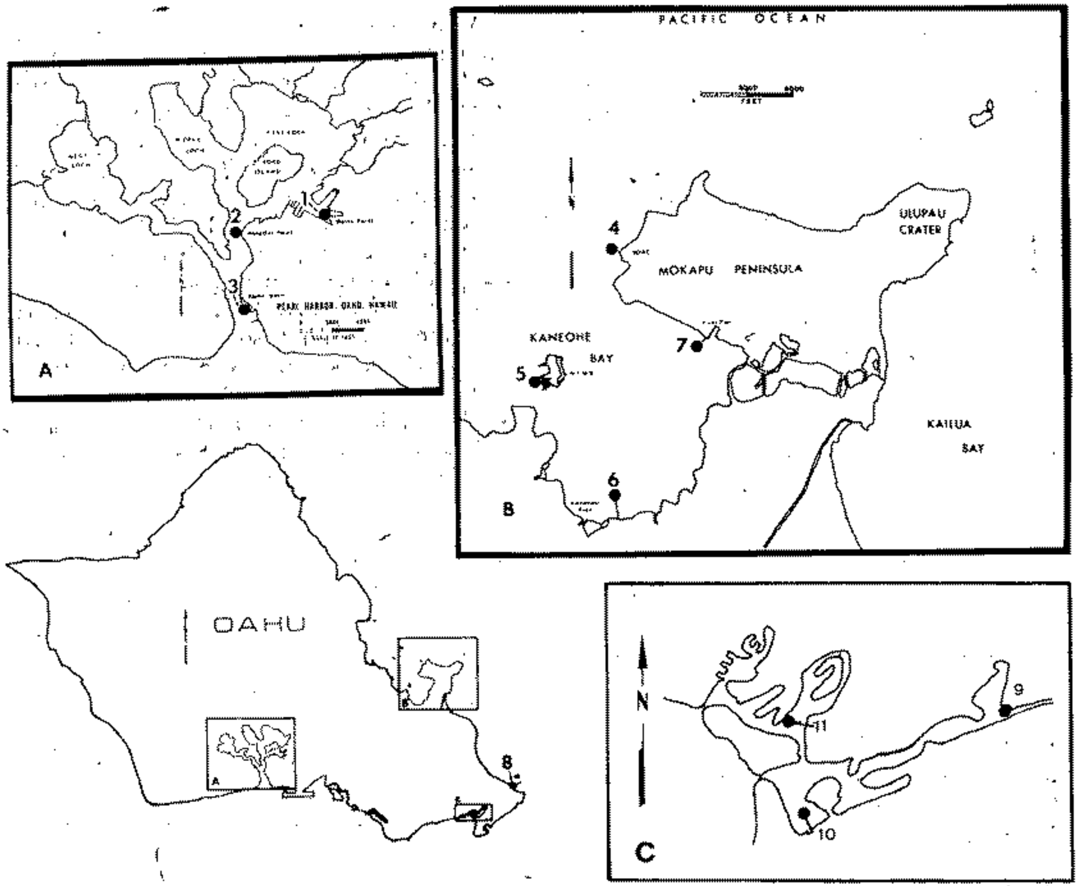

FIG. 1.—Location of Study Sites at Oahu, Hawaii.

in the six-months series is basically the same, the most important variable is still surface cover. Compound tunicates are also important, as in the Pearl Harbor and Kaneohe Bay stations of the three-months series, but to a much lesser extent. Figure 4 is a graph of the number of teredinids versus surface cover.

Only at Station 8, Makai Range, were enough specimens available for a size-frequency distribution suitable for evaluating the temporal pattern of teredinid settlement. This was only attempted for the three-months-series, it being impossible to sample the teredinids from the riddled blocks of the six months series. It was noted, however, that a major proportion of the high numbers encounter in these samples resulted from very small individuals, 1 mm in shell diameter, indicating recent heavy settlement. Since stunted growth due to crowding was unlikely (even at this station most of the wood remained unbored in the three-months series) the size of the specimens was considered to be proportional to their age, although the exact growth rate could not be calculated from our data. An approximation was made that *L. affinis* with valve diameters of 4 mm or larger would represent settlement during the first month of exposure, 2-4 mm the second month, and less than 2 mm, the last month. This is likely to be a conservative estimate for the smaller individuals. The size-frequency distributions of *L. affinis* and the

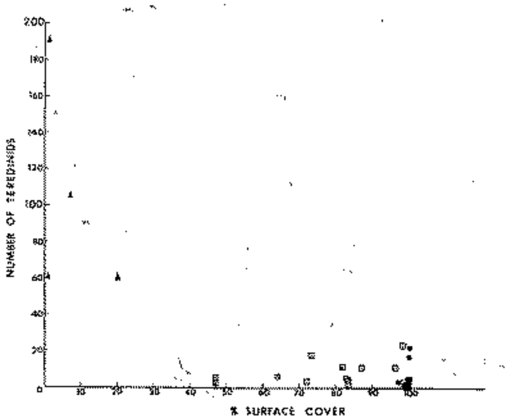

FIG. 2.—Number of teredinids (all species) versus percent surface cover for the three-months exposures. Solid Circles, Pearl Harbor; Squares, Kaneohe Bay; Triangles, Sta. 8, Makai Range.

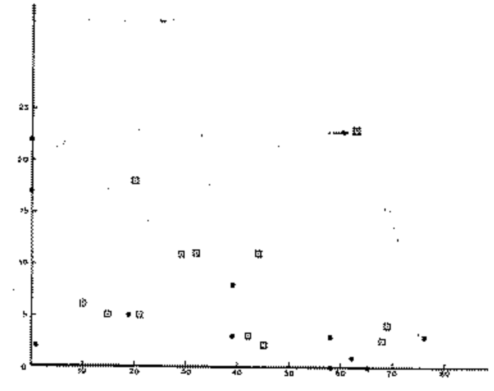

FIG. 3.—Number of teredinids (all species) versus percent frequency of compound tunicates at Kaneohe Bay and Pearl Harbor Stations only for the three-months exposures. Solid Circles, Pearl Harbor; Squares, Kaneohe Bay. Arrow indicates divergent value removed from regression calculations.

number brooding during each series at Station 8 are presented in figure 5. In series I and IV two peaks in abundance suggest that heavy settlement could have occurred at least twice during those exposures. During the other series settlement appeared to have occurred rather evenly during series II, and with one major peak during series III. In all cases, small individuals (less than 2 mm in shell diameter, presumed to be less than one month old) were present in significant numbers.

At Station 8, the smallest individual with brooding embryos was approximately 3.5 mm in shell diameter, and 33 % of the specimens in the 3.7 mm size class (where brooding was first common) or larger were brooding. The limited number of *L. affinis* recovered from the other stations were generally larger; smaller individuals were completely lacking, as is shown in the top graph of figure 4. None of the *L. affinis* found at the other stations were brooding although many were of sufficient size. The other teredinid species recovered from the Pearl Harbor and Kaneohe Bay stations were also larger individuals, with no very small individuals present. Only one teredinid, a *Lyrodus pedicellatus* at Station 6, series I, was found brooding at these stations. The size-frequency distributions and size at breeding for other species could not however, be directly compared without the unwarrented assumption of equal growth and reproductive rates in all teredinid species.

The pattern for *Limnoria tripunctata* occurrence and abundance is similar to that for the teredinid borers, but more extreme. Only Station 8 had extensive *Limnoria* activity (tunnels) and high numbers of *Limnoria tripunctata* during the three-months series. Numbers of *L. tripunctata* recovered during the different series at Station 8, ranging from a low of 8 specimens recovered from a block with a frequency of 5.1 % *Limnoria* tunnels to a high

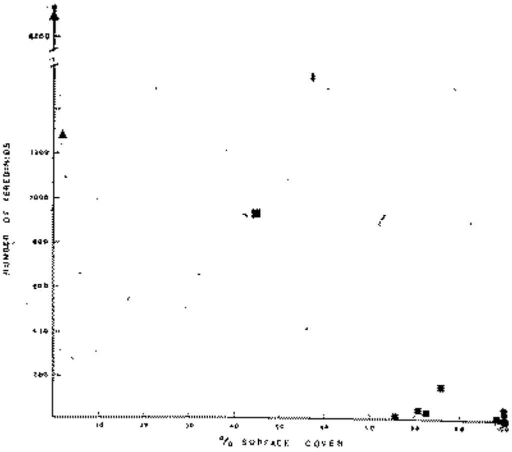

FIG. 4.—Number of teredinids (all species) versus percent surface cover for the six-months exposures. Solid Circles, Pearl Harbor; Squares, Kaneohe Bay; Triangles, Sta. 8, Makai Range.

count of 1258 specimens recovered from a block with a *Limnoria* tunnel frequency of 75 %. *Limnoria* tunnels were observed on four blocks from Pearl Harbor and Kaneohe Bay where no *Limnoria* specimens were recovered. *L. tripunctata* specimens were, however, recovered from three blocks (2III, 3II and 5IV) where the frequency of tunnels was too low to be sampled in the grid count method. It seems unlikely then that the *Limnoria* tunnels present in the blocks at Station 1, series I and IV; Station 4, serie III; and Station 5, serie I, actually contained live *L. tripunctata.* Presumably, these tunnels were the result of *L. tripunctata* populations which had existed earlier during the exposure period. During the six-months series Station 8 again had the highest numbers of *L. tripunctata,* 4834/block, although Station 6 and Station 7 also had high numbers. Results of the multiple stepwise regression for *L. tripunctata* against factors of the surface community are presented in Table 6. Surface cover and compound tunicates are again indicated as having a significant effect on the success of *L. tripunctata.*

The results from Hawaii Kai indicate a more complex situation than was present at the other stations. Five of the six blocks from Hawaii Kai had extremely high numbers of *L. tripunctata,* and very high *Limnoria* tunnel frequencies (F_c). Coincident with this was the reduction of the surface cover to low values, although from the development of those portions still attached, it appears than surface cover at these stations was extensive earlier in the exposure period. In two of the blocks, the surface area has been reduced to nearly half the original (552 cm², 546 cm²) due to exfoliation of the wood. In spite of this reduced cover, the number of teredinids is rather low.

Low numbers of teredinids were recovered from the blocks exposed in the Ulupau facility although this was the longest exposure period. Not surprisingly, these blocks had no *Limnoria tripunctata,* as would be expected, given the dispersal capabilities of *L. tripunctata* as discussed below.

As expected, drift wood samples contained a oceanic fouling, dominated by *Lepas* spp. with none of the common foulers from the nearshore stations being present. The only teredinid species found in this drift material were *L. affinis,* and *Teredora princessae,* the later species, being unknown at the nearshore stations.

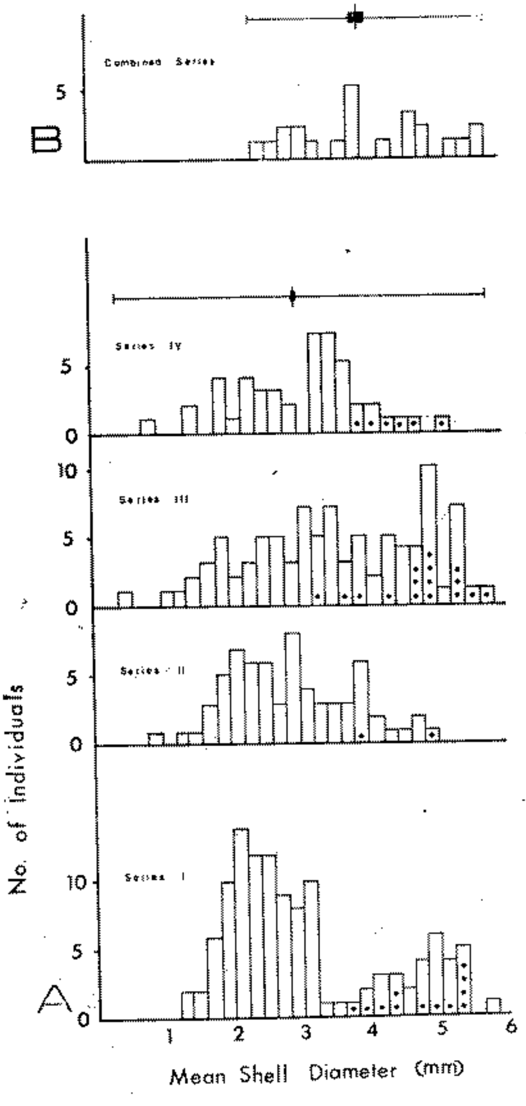

FIG. 5.—Size-frequency distribution of *Lyrodus affinis* from each three-month series at Sta. 8, Makai Range, and from all series at Pearl Harbor and Kaneohe Bay three-month series. Mean, standard error, and range indicated for all series Sta. 8 (A) and for all others combined (B). Brooding individuals represented by dots.

TABLE 5

MULTIPLE REGRESSION ANALYSIS OF COMPONENTS OF THE SURFACE FOULING WITH SIGNIFICANT ($p < .01$) EFFECTS ON THE ABUNDANCE OF TEREDINID BORERS

Cases	*Dependent variable*	*Regression coefficient*	*Multiple corr. coeff.*	*% variance reduced*	*F value*
Case I					
All three month Stations # teredinids/block.	% surface cover	—68.6	.74	54	30.6 **
	Hydroids	—58.8	.78	7	19.3 **
		Computed equation: $Y = 104.7 - 67.3X_1 - 57.3X_2$			
Case II					
Pearl Harbor Kaneohe Bay Stations only (3 months) # teredinids/block.	Compound tunicates	—13.0	.63	40	13.8 **
	Hydroids	—14.2	.73	15	10.5 **
	Bryozoans	12.0	.79	8	9.0 **
		Computed equation: $Y = 13.8 - 13.0X_1 - 14.2X_2 + 12.0X_3$			
Case III					
Pearl Harbor Kaneohe Bay Stations (6 months) # teredinids/blocks.	% surface cover	—5955	.78	.60	15.1 **
	Compound tunicates	—2825	.85	.73	12.4 **
		Computed equation: $Y = 9498 - 5955X_1 - 2825X_2$			

Only those components with greater than 5 % variance explained included.

DISCUSSION

Three lines of evidence support the contention that the success of the borer community is reduced by the presence of a well-developed surface fouling community: first, the great differences in the success of the major borers (teredinids and *L. tripunctata*) under different fouling communities; second, time of settlement versus success of the teredinid borers; and third, the reproductive success of the teredinid borers in fouled blocks.

Successful and heavy teredinid and *Limnoria tripunctata* communities developed in three months only at Station 8, Makai Range, where a typical epifaunal fouling community was lacking. At the other sites in Pearl Harbor and Kaneohe Bay, few teredinids and even fewer

TABLE 6

MULTIPLE REGRESSION ANALYSIS OF COMPONENTS OF THE SURFACE FOULING WITH SIGNIFICANT ($p < .01$) EFFECTS ON THE ABUNDANCE OF "LIMNORIA TRIPUNCTATA"

Case	*Dependent variable*	*Regression coefficient*	*Multiple corr. coeff.*	*% variance reduced*	*F value*
Case IV					
Pearl Harbor Kaneohe Bay Stations (months) ≠ *L. tripunctata*/block.	% surface cover	—2560	.91	.82	45.9**
	Compound tunicates	—1233	.94	.89	34.6**
		Computed equation: $Y = 4046 - 2560X_1 - 1233X_2$			

Only those components with greater than 5 % variance explained included.

L. tripunctata established in and survived for the same period of time. Other sites however, also developed reasonably heavy borer communities in six-months, provided the surface cover was not too heavy. Unavailability of teredinid larvae does not seem a likely explanation for their low numbers at the other seven stations in Pearl Harbor and Kaneohe Bay. Teredinid settlement did occur at all these stations during every series except series I and II at Station 2, indicating that environmental conditions in the surrounding water were within larval tolerances, and that teredinid veligers were present throughout the year. Since during series I and II Station 1 (further inside Pearl Harbor) and Station 3 (near the entrance) had teredinids, larvae were available at Station 2. Additionally, previous authors (EDMONDSON and INGRAM, 1939; LONG, 1972) have reported extensive teredinid damage (after longer exposures) in Pearl Harbor and Kaneohe Bay. Similarly, the high teredinid numbers at Stations 5 and 6 in the six-months exposures in Kaneohe Bay demonstrate the general suitability of this area for borer larvae, but Station 7 with heavier surface coverage had far fewer teredinids.

Lack of surface fouling, however, does not guarantee heavy teredinid boring, as evidenced by the Hawaii Kai and Ulupau samples. In Hawaii Kai, the extremely high *Limnoria tripunctata* densities appear to be detrimental to both the teredinids and the surface fouling [similar to the findings of FUNG and MORTON (1976)]. At Ulupau, the reasons for the low settlement can not be readily explained, although low larval availability near the reef flat, pump and entrainment damage, as well as factors of the exposure, light level, water motion, etc., could all play a part. Certainly, though this verifies that borer settlement can be monitered in microcosm systems, and variable manipulated in future experiments.

Just as the success of teredinids is influence by the surface fouling, so is the success of *L. tripunctata*, and presumably other *Limnoria* in general. Indeed, *Limnoria* may be more sensitive since it concentrates its boring closer to the surface than the teredinids do. Since *Limnoria* young are brooded with the female and there is no planktonic dispersal phase, *Limnoria* colonization must rely on fortuitous drift, or whatever swimming capabilities the adults possess. The availability of *Limnoria* at these stations can not be evaluated with our limited data. However, since *Limnoria* infested pilings and other timber is abundant in Pearl Harbor and Kaneohe Bay, *Limnoria* availability is not likely to be less than at Station 8 on an open coast with no extensive timber structures nearby. The fact that *L. tripunctata* (tunnels or specimens) were found at all stations except 6 and 7 supports the general availability of *L. tripunctata* in both Pearl Harbor and Kaneohe Bay.

Secondly, the size-frequency distribution of the borers in Pearl Harbor and Kaneohe Bay supports the contention that these are individuals which settled and entered the wood before the surface community was extensively developed. NAIR (1962) discusses how teredinid borers already established within the wood can co-exist with extensive surface fouling. Similarly, the presence of *Limnoria* tunnels without *L. tripunctata* specimens is consistent with similar early *L. tripunctata* settlement before the development of extensive surface fouling. *L. tripunctata* apparently can not co-exist with a well developed fouling community as the teredinids do. The exact mechanisms responsible for the loss of the *L. tripunctata* populations, whether physical interference, overgrowth of tunnels and accessory breathing holes, or predation by other species in the complex fouling communities, is unclear.

Only one of the 186 teredinids (a *L. pedicellatus*) from the Pearl Harbor and Kaneohe Bay stations during the three-months series was found brooding. During the same period of time, a much higher proportion of the individuals at Station 8 were brooding larvae. Since most of the individuals found at the other stations were of sufficient size to be reproductively mature (fig. 5) (EDMONDSON, 1942; TURNER, 1966), the lack of breeding likely results from the low densities in the Pearl Harbor and Kaneohe blocks. Successful reproduction is probably very uncommon at these densities (maximum approximately 1 per 100 cm^3) while it seems common at the densities (minimum approximately 1 per 35 cm^3) encountered after only three months at Station 8. Reproduction would be particularly hindered in the presence of heavy fouling if pseudo-copulatory or siphonal copulatory behavior (CLAPP, 1951, cited in TURNER, 1966) was necessary in these species. Even if copulation were not required, and sperm were shed externally, the low densities and interference and feeding on the gametes by the fouling community would still tend to reduce the breeding success. Those few borers which entered wood which became heavily fouled may be considered lost to the breeding populations unless densities increased during longer exposure, perhaps by temporary disruptions of the surface fouling and new borer settlement.

The selection and relative importance of the various factors affecting borer success (Tables 5 and 6) must be considered preliminary, indicating which interactions may bear closer examination. The biology of the surface foulers, influenced as they are by many common factors produces independent variables which are significantly auto-correlated.

Evidence strongly suggests that the simple physical blocking of the surface, regardless of the particular fouling taxa involved, is of great importance, especially when the total range of fouling intensities which may be encountered in any geographic location is considered. Fouling makes the surface layer of the wood, and hence the bulk of the wood unavailable to settling borer larvae. The importance of physical blocking of settling larvae is reinforced by the correlation of reduced borer numbers with high frequencies of compound tunicates whose major effect must be physical interference. Since these tunicate species are microfilterers, and would probably not ingest borer larvae their interactions must result from their mere presence on the surface. These species have a rapidly spreading colonial growth form, tightly adherent to the surface. They would present a formidable barrier to settling larvae, but not to established adults whose siphons could extend past the 2 mm-3 mm thick colonies. Because of these many co-related variables our data do not unambiguously extract the particular causal mechanisms which reduce the success of the borers.

Our finding of reduced borer success under certain fouling is in agreement with the findings of WEISS and NAGABHUSHANAM (1960) who reduced fouling coverage by periodically scrapping their test block surface. WEISS (1948) did not report actual numbers. NAGABHUSHANAM (1960) demonstrated approximately a nine fold difference between the numbers of teredinids in fouled versus weekly cleaned blocks, but the amount and composition of this surface fouling was not reported. NAIR (1962) also found the lightest borer settlement on blocks fouled by tubicolous polychaetes and amphipods. However, his conclusions are complicated by the wide range of hydrographic conditions at his stations, and the much longer exposure time and slower community development in the cold temperate waters.

Unexpectedly, several other important components of the fouling community seem to have little influence on the success of the borer community. Test blocks with fouling communities dominated by barnacles, serpulid polychaetes, bryozoans and hydroids still had significant borer numbers. The overall biomass of the fouling community also seems to have only a minor effect.

This suggests that greater insight into the effect of the surface fouling community on the success of borer attack could be achieved by further investigations focused on the biology of particular foulers and their interaction with the settling larvae of the borer species. Competition appears to be focussed, even in these species with basically different requirements for the resource, at the point where both epifaunal and borer species are most similar in their use of the resource, spatially, as a site to settle and metamorphose. It also suggests that earlier confusion about the effect of surface fouling community on borer success results from examining fouling communities, with different dominant species, not all of which influence borer success to the same degree. Various levels of surface disturbance, the temporal pattern and sequence of larval settlement and larval patchiness and swamping must also influence community composition. In general, while the absence of fouling (with suitable borer larval availabilify) will surely result in heavy boring, the presence of rather heavy fouling, of certain kinds, is not particularly detrimental to the borers, and will not protect wood from boring attack.

Clearly, the rapid development of certain fouling communities can monopolize the surface of the wood as a spatial resource and by prolonging the existence of this substratum extend their own existence. The composition of the total community on and in wood is thus effectively modified by the success of many different species with basically different uses of the same resource.

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SETTLEMENT AND GROWTH OF THE FOULING ORGANISMS AT ALAMEDA MARINA, SAN FRANCISCO BAY, CALIFORNIA

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ABSTRACT

Settlement and growth of the fouling organisms at Alameda Marina, San Francisco Bay, California, were examined from January 1, 1975, to May 18, 1976. Plastic plates suspended in a rack were exposed at a constant depth and retrieved at 1, 2, 6, and 12 month intervals. Organisms settling during these periods were identified and numbers and size of certain taxa were recorded. Particular seasons of settlement were inferred from when the taxa attached to the plates.

There was a marked seasonal fluctuation in abundance and also a difference in the year-to-year abundance of certain taxa. The total number of attached taxa, and the number and size of certain of the taxa were found to be correlated with water temperature changes.

Our findings were compared with those of GRAHAM and GAY (1945) who worked on the fouling organisms in the Oakland Estuary, near our study site. The abundance and composition of the attached organisms were quite different between the two studies. Some possible explanations are discussed.

The Quotient of Similarity (SORENSON, 1948) was used to compare the total number of taxa that attached after 1, 6 and 12 month periods. The data indicates that organisms did not disappear as the community developed, and settlement was dependent on when the larvae or spores were in the water. This development of the community was interpreted as a seasonal progression, instead of a true succession.

INTRODUCTION

Studies of fouling organisms have provided a wealth of information about the interrelationships of organisms inhabiting these unique communities. Of particular interest are those studies which examine not only the species composition and structure but also the development of the community through time (ANGER, 1978; BOYD, 1972; OSMAN, 1977; SUTHERLAND, 1974; SUTHERLAND and KARLSON, 1977, and others).

It is not clear if community development in the marine environment takes place via true succession or by seasonal progression. For true succession to occur, 1) earlier organisms in the community must be essential to the attachment of later ones, and 2) organisms must disappear as the development of the community progresses (SHELFORD, 1930). Investigators (COE, 1932; COE and ALLEN, 1937; FAGER, 1971; HADERLIE, 1968, 1969, 1974, and others) have attempted to follow this community development by using man-made substrates (settling plates) such as glass, plastic, wood, asbestos, concrete, metal and painted surfaces. The temporal pattern or season of settlement of organisms can be determined by noting the presence or absence of each individual species during periodic plate sampling. SCHEER (1945) demonstrated that when bacteria were present on glass plates, there was increased settlement of hydroids. He also found that the settlement sequence did not depend on when the plates were exposed, and argued that development must have been via a true succession. Other investigators (BOYD, 1972; KAWAHARA, 1962, 1963, 1965; OSMAN, 1977, and others) found

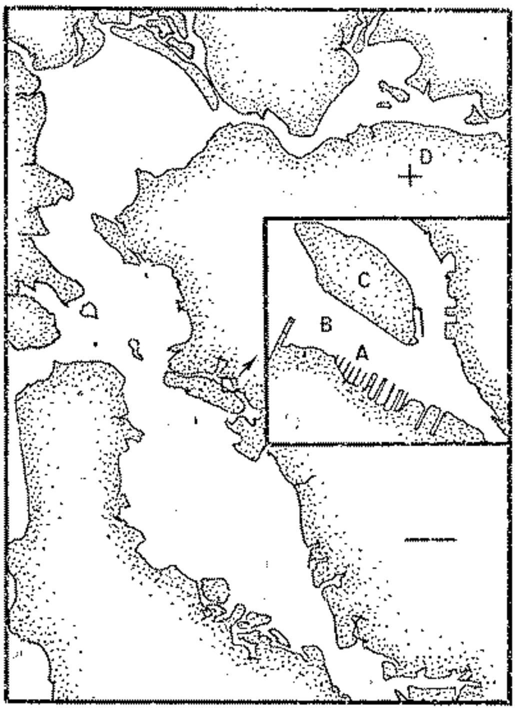

FIG. 1.—Map of San Francisco Bay. Insert shows Alameda Marina (A), Oakland Estuary (B) and Government Island (C). At point D, Latitude is 38° 00' N and Longitude is 120° 00' W. Total scale equals 4 miles.

that settlement depends on the order of arrival of larvae and spores, and the presence of one organism is not essential for the attachment of others.

To our knowledge, only one study has been carried out on the fouling organisms of San Francisco Bay, that of GRAHAM and GAY (1945) in the Oakland Estuary. They found the community on wood to be dominated by *Tubularia crocea* (Hydrozoa), *Polydora ligni* (Polychaeta), *Corophium insidiosum* (Amphipoda), *Balanus improvisus* (Cirripedia) and *Mytilus edulis* (Pelecypoda). The settlement of most of the organisms in their study appeared to be related to the changes in water temperature.

The purpose of our study was to examine the following four questions: (1) What was the season of settlement of the fouling organisms at Alameda Marina, Oakland Estuary, San Francisco Bay? (2) What was the growth rate of certain of these fouling organisms? (3) Was the season of settlement or growth rate related to either water temperature or salinity changes? (4) Did development take place via a true succession or by a seasonal progression?

MATERIAL AND METHODS

The study was carried out from January 1, 1975, until May 18, 1976, at Alameda Marina, Alameda, California. This Marina is located on the Oakland Estuary, across from Government Island (Fig. 1) and is within one mile of GRAHAM and GAY's (1945) study site.

Experimental fouling surfaces, 10 × 10 cm, were constructed of 5 mm thick black acrylic sheeting sandblasted to roughen the surface (crevices about 0.1 mm wide and deep) and aid in the attachment of the organisms (POMERAT and WEISS, 1946). Five sets of plates were used, with three replicates per set as follows: (A) plates that were exposed for one month, (B) and (C) plates that were exposed for two months, (D) plates that were exposed for six months, and (E) plates that were exposed for twelve months. Two plate types, (B) and (C), were needed for the two month exposure so that one set could be collected at the end of each two month period. Table 1 illustrates the chronological sequence of placement and replacement of the plates.

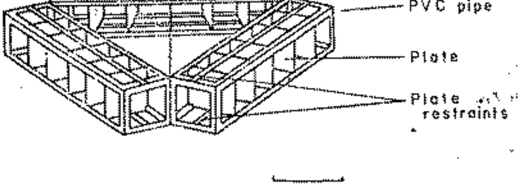

FIG. 2.—Rack with fifteen plates in place. Scale equals 15 cm.

TABLE 1

SCHEDULE OF PLATE PLACEMENT AND REPLACEMENT

Year	1975														1976				
Month	1	1	2	3	4	5	6	7	8	9	10	11	12	12	1	2	3	4	5
Date	1	29	26	26	23	21	18	16	13	10	8	5	3	31	28	25	24	21	23
1 month plates (A) ...	P →	R →	R →	R →	R →	R →	R →	R →	R →	R →	R →	R →	R →	R →	R →	R →	R →	R →	R
2 month plates (B) ...	P →		R →		R →		R →		R →		R →		R →		R →		R →		R
2 month plates (C) ...	P →	R →		R →		R →		R →		R →		R →		R →		R →		R →	
6 month plates (D) ...	P →						R →						R →						R
12 month plates (E) ...	P →												R →						

P: Placement of plates.
R: Replacement of plates.

The plates were held in a rack constructed of rigid, white 1 inch PVC tubing held together with waterproof PVC glue and stainless steel hose clamps and filled with concrete to create a negative bouyancy (Fig. 2). The rack held 15 randomly positioned plates oriented vertically at a constant distance of 5 cm from each other. A stainless steel cable (5 mm diameter) suspended the rack at a constant depth of 76 cm from the surface of the water. The cable was hooked to the rack via a swivel which enabled the rack to turn with water movement.

Each «month» (28 days) the appropriate set of 1, 2, 6 and/or 12 month plates was collected from the rack and clean, randomly selected plates were used to replace the collected plates. All organisms were identified, listed, and size and numbers of certain taxa (quantified) were recorded. The plates were reused after being cleaned of all living material.

Temperature and salinity were monitored during the study by use of a hand-held thermometer and a refractometer, respectively.

The mean size of the three largest individuals of each of the quantified taxa attached to the 1 and 2 month plate sets was calculated. It was assumed that the largest individuals of each taxa attached on the day the clean plates were placed in the water. Size of encrusting animals (bryozoans and colonial tunicates) was determined with a planimeter and expressed as total area covered (mm²). Areas less than 25 mm² were estimated. Size of upright animals (barnacles, mussels and simple tunicates) was determined by use of a micrometer and expressed in millimeters. Simple tunicates were relaxed before measuring.

Correlation coefficients (Zar, 1974) were calculated to determine if the total numbers of, or mean size of individuals of the quantified taxa, or the total number of attached taxa were related to temperature and/or salinity changes.

A comparison, using the Quotient of Similarity (Sorenson, 1948) was made between the total number of taxa that attached after different lengths of plate submergence to determine if the development of the fouling community took place via a true succession or by a seasonal progression.

RESULTS

The season of settlement of the fouling organisms at Alameda Marina is shown in Figure 3. Only «diatom film» (probably composed of at least bacteria, diatoms, fungi, algal spores and newly attached invertebrate larvae) and *Melosira* spp. attached every month throughout the study. Certain taxa (i.e. *Zoothamnium* spp., *Obelia longissima*) did not attach during the summer, while others (i.e. *Halichondria bowerbankia* and *Botryllus* spp.) did not settle during the winter.

The quantified taxa were the bryozoans *Membranipora membranacea, Cryptosula pallasiana, Smittoidea prolifica*, the barnacle *Balanus improvisus*, the polychaete *Mercierella enigmatica*, the mussel *Mytilus edulis*, and the tunicates *Botryllus* spp., *Botrylloides* spp., *Ascidia ceratodes, Molgula manhattensis* and *Ciona intestinalis*. One additional category, family Botryllidae, was used for all colonial tunicates that could not be identified to genus. The total numbers of individuals of these quantified taxa that attached to each set of 1 month plates during the study are shown in Figure 4. These counts were based on pooled data from three 1 month plates, which represents a combined plate surface area of 600 cm². None of these taxa settled all year long. Peak settlement for each taxa was during the spring or summer. For a few taxa there was a difference in the number of individuals settling during the two years. Data from the 2 month plates showed similar trends in settlement periods as those found on the 1 month plates.

Two foliose bryozoans, *Tricellaria occidentalis* and *Bugula californica*, although not quantified, were noted to have a fairly heavy settlement (approximately 10-25 individuals per 1 month plate face) from July to September of 1975. No *B. californica* attached in 1976.

Figure 5 shows the mean size ± 1 standard error of the three largest individuals of eleven of the quantified taxa that attached to the sets of 1 month plates. No size data was recorded for *Mercierella enigmatica*. Maximum taxa growth appears to take place during the spring and summer. Data from the 2 month plates showed similar trends to the 1 month plate data.

Figure 6 shows the total number of taxa

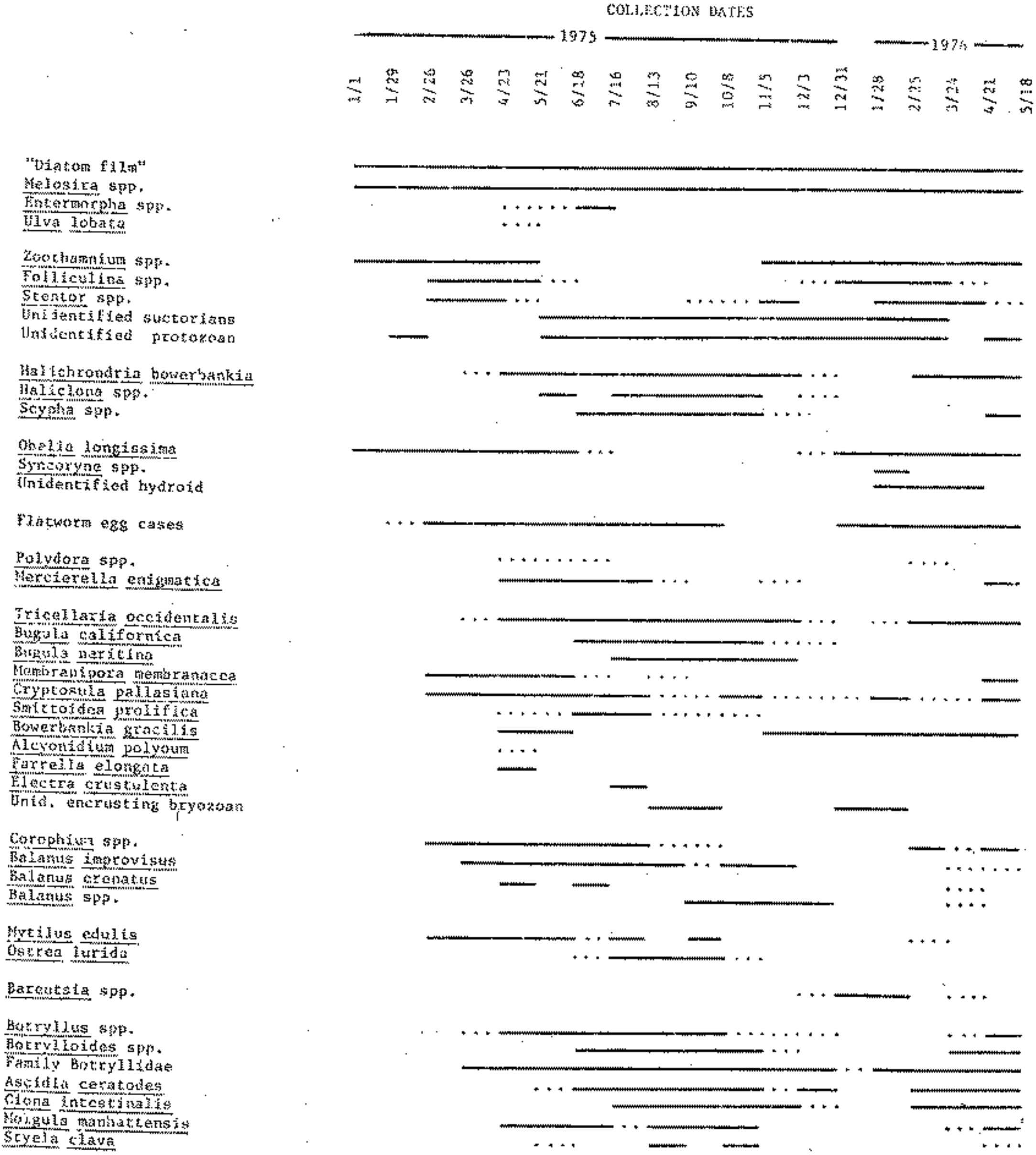

FIG. 3.—Settlement periods of the fouling organisms at Alameda Marina. Solid lines indicate settlement on both 1 and 2 month plates; dotted lines, settlement only on 2 month plates.

that attached to each set of 1 month plates during the study. The maximum attachment period was during the spring and summer, while settlement decreased during the winter.

Water temperature and salinity fluctuations at Alameda Marina are plotted in Figure 7. As expected, the temperature was highest during the summer and lowest during the winter. Winter and spring rains during 1975 caused a drastic decrease in the water's salinity. This

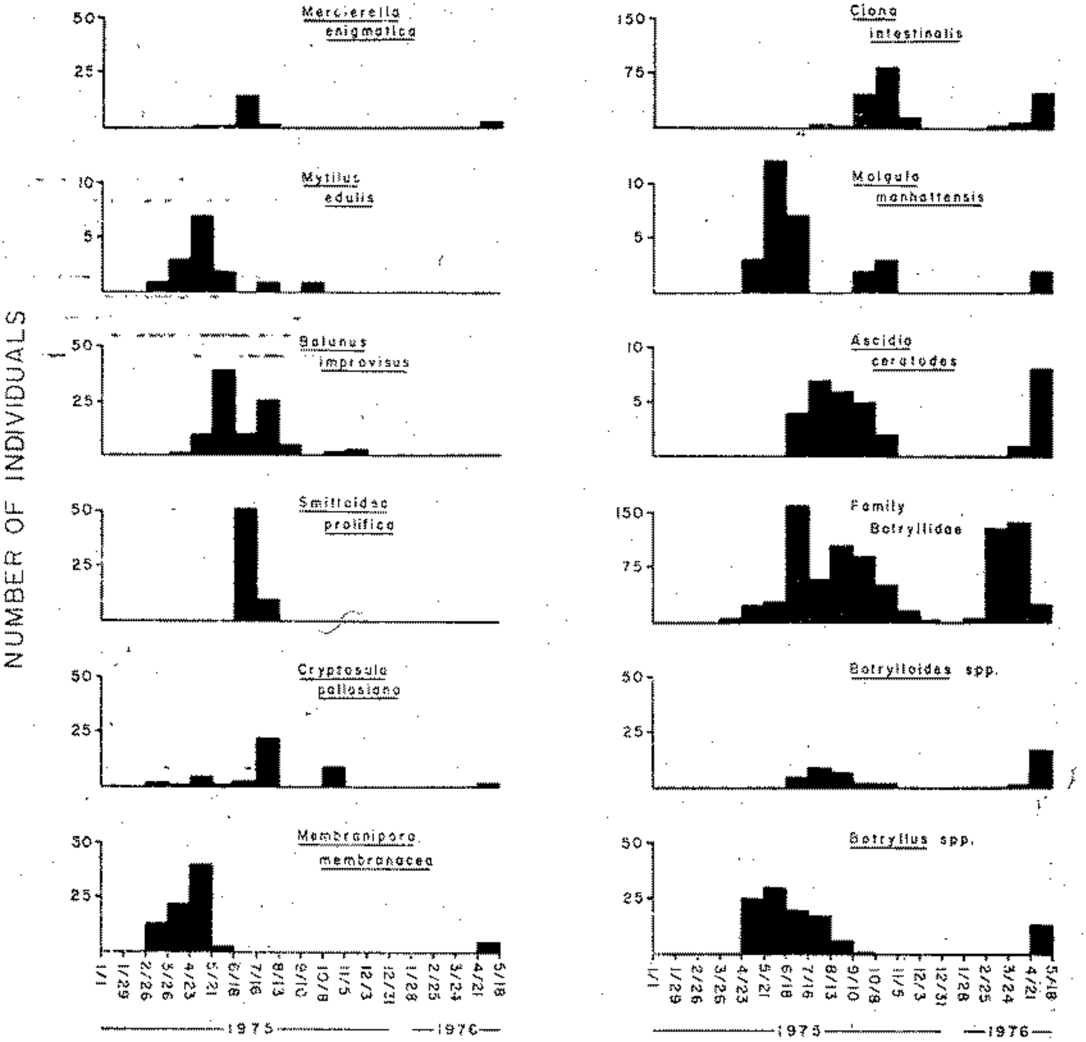

FIG. 4.—Total number of each of the quantified taxa that attached to each set of 1 month plates during the study. Total available settling surface per set of plates was 600 cm².

decrease in salinity did not take place during the same period in 1976 due to a lack of rain.

The correlation coefficients (Table 2) show that the total number of attached *Balanus improvisus, Botryllus* spp., *Botrylloides* spp., family Botryllidae, *Ascidia ceratodes,* and *Molgula manhattensis,* and the mean size of *Balanus improvisus, Cryptosula pallasiana, Botrylloides* spp., family Botryllidae, *Ascidia ceratodes* and *Ciona intestinalis* were positively correlated with water temperature ($P < 0.05$). The total number of *Botrylloides* spp. and *Ascidia ceratodes* and mean size of *Ciona intestinalis* were positively correlated with salinity changes, while the total number of *Membranipora membranacea* and *Mytilus edulis* and mean size of *M. membranacea* were negatively correlated with salinity changes ($P < 0.05$). Similar findings were obtained from the 2 month plate data.

The correlation coefficients also show that

TABLE 2

CORRELATION COEFFICIENTS FOR THE TOTAL NUMBER OR MEAN SIZE OF THE QUANTIFIED TAXA ON EACH SET OF ONE MONTH PLATES VERSUS WATER TEMPERATURE AND SALINITY CHANGES

	NUMBER VS.		SIZE VS.	
	Temperature	*Salinity*	*Temperature*	*Salinity*
Mercierella enigmatica	.434	.073	ND	ND
Membranipora membranacea	—.048	—.724 *	.115	—.562 *
Cryptosula pallasiana	.453	.065	.532 *	.031
Smittoidea prolifica	.391	.045	.407	.053
Balanus improvisus	.526 *	—.010	.570 *	—.216
Mytilus edulis	.111	—.618 *	.431	—.114
Botryllus spp.	.594 *	—.052	.413	—.055
Botrylloides spp.	.592 *	.476 *	.620 *	.348
Family Botryllidae	.621 *	.416	.872 *	.245
Ascidia ceratodes	.765 *	.517 *	.693 *	.292
Ciona intestinalis	.358	.299	.541 *	.480 *
Molgula manhattensis	.471 *	—.042	.448	—.017

* Significant at $p = 0.05$.

ND: No data.

the total number of attached taxa on the sets of 1 month plates were significantly correlated to water temperature changes ($r = 0.919$; $r_{0.05\,[2],\,16} = 0.468$), but not significantly correlated with salinity changes ($r = 0.185$). The 2 month plate data showed similar test results.

A dendrogram, constructed by using the unweighted pair-group average method, portrays the similarity between the taxa lists of all the 1 month, 6 month and 12 month plate sets during 1975 (Fig. 8). There are two major groupings with the division chronologically coming between the June and July 1 month plates. The August 1 month plates are more similar to the December 6 and 12 month plates than to any of the other 1 month plates. Likewise, the June 1 month plates are more similar to the June 6 month plates than to any other plates.

DISCUSSION

The initial fouling community that developed on the experimental plates at Alameda Marina was composed of numerous taxa, many of which showed a distinct seasonal settlement. The protozoans and hydroids settled mainly during the winter, while most of the other organisms attached during the spring, summer and sometimes into the fall. There was a marked seasonal fluctuation in abundance of all of the quantified taxa and a difference in the year-to-year abundance of *Membranipora membranacea, Balanus improvisus, Mytilus edulis,*

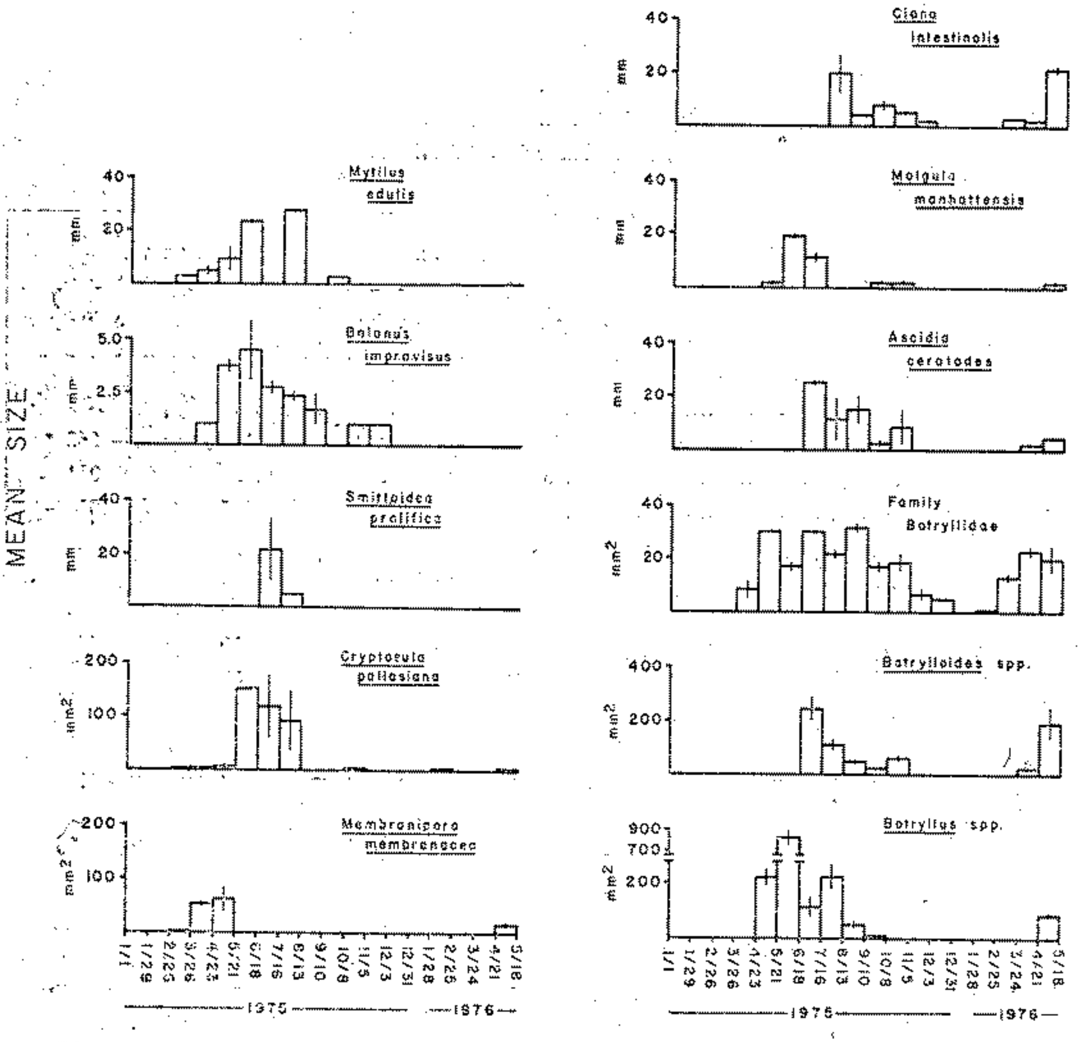

FIG. 5.—Mean size ± 1 Standard Error of the three largest individuals of eleven of the quantified taxa that attached to the sets of 1 month plates.

Botrylloides spp., family Botryllidae, *Ascidia ceratodes*, *Molgula manhattensis* and *Ciona intestinalis*.

Organisms respond to their total environment but it is «extremely difficult to describe and evaluate details of the complex relationship between an organism and its environment particularly since it is virtually impossible to measure simultaneously all physical, chemical and biological aspects of the environment of an aquatic organism under ecological conditions» (KINNE, 1963).

Many factors could possibly affect spore and larval attachment. Physico-chemical factors include type, color, texture, orientation, and depth of the substrate, water current moving over the substrate, presence of silt, presence of pollutants, time of year, length of submergence, quality and quantity of light, water temperature and salinity. Biological factors in-

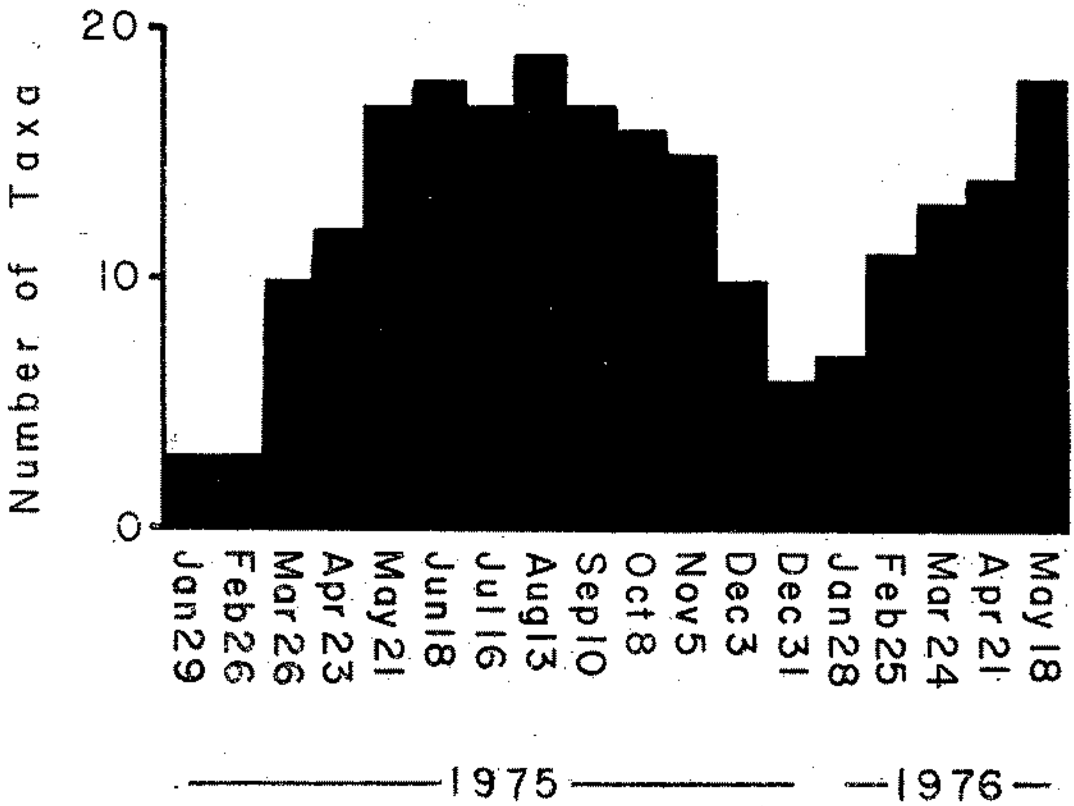

FIG. 6.—Total number of taxa that settled on each set of 1 month plates throughout the study.

clude competition for space and light, predation, grazing, abundance of spores and larvae in the water column, time of spore or larval arrival, selectivity of larvae to the site of attachment, and presence of the same or a different species on the substrate.

Water temperature changes have been found to regulate both the growth rate and the numbers of newly attached individuals of marine organisms (ORTON, 1920; COE and ALLEN, 1937; NICOL, 1960). It is known that spawning in many marine organisms is triggered by either a certain temperature or a definite temperature change, which varies with species (KINNE, 1963; VERNBERG and VERNBERG, 1972). Within any one species, the breeding season varies in different parts of its range depending on the temperature variations at different latitudes (Woods Hole Oceanographic Institution, 1952; CRISP, 1957; SASTRY, 1963). This is the probable reason why certain species in the study started to settle at a different temperature than has been observed by other investigators. It is not certain why two species (*Balanus improvisus* and *Corophium* sp.) started to attach at 15° C at Oakland (GRAHAM and GAY, 1945), and at 11° C at Alameda. It is possible that the increased amount of pollution in 1945 (see below) put an added stress on these organisms either as adults and/or larval stages, and thus they did not begin settlement until a slightly higher temperature was reached.

SUTHERLAND (1974), studying the fouling organisms at Beaufort, North Carolina, found that there was a distinct seasonal pattern of species recruitment associated with seasonal temperature fluctuations. In the present study, the correlation coefficients demonstrate that changes in the total number of attached taxa, the total number of attached individuals of

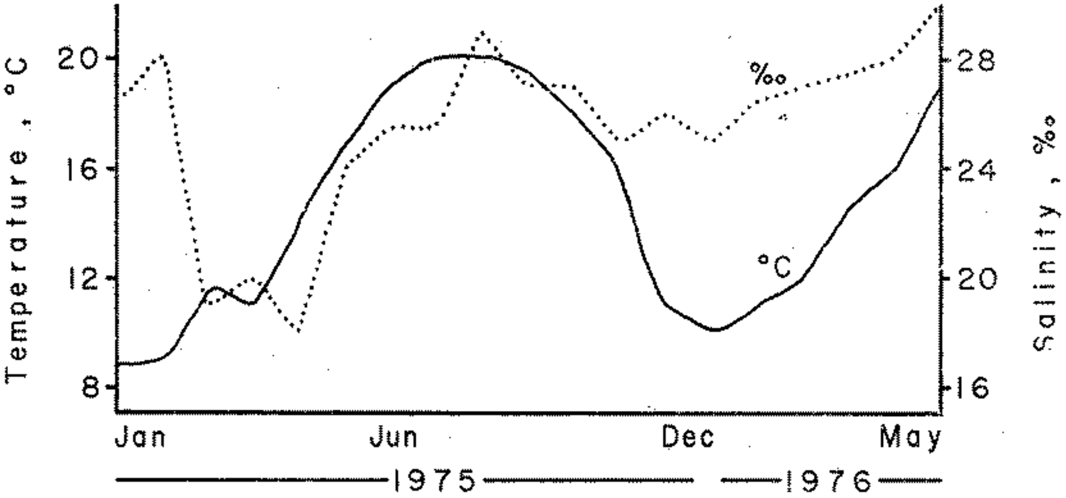

FIG. 7.—Water temperature and salinity fluctuations at Alameda Marina.

six taxa, and the mean size of six taxa were directly correlated with water temperature changes.

McDOUGALL (1943) found that high summer temperatures tended to stop reproduction in *Molgula manhattensis.* This also takes place in other organisms (Woods Hole Oceanographic Institution, 1952). During the warmest water period at Alameda, the number of attached *M. manhattensis* on the 1 month plates dropped to zero.

NAIR (1967) found that salinity variations played a major role in settlement and growth of the major fouling organisms in Cochin Harbor, India. ORTON (1920) found that salinity had no affect on the breeding of many marine organisms. We found that salinity was positively correlated with the total number of attached individuals of two taxa and the mean size of one taxa. It was also negatively correlated with the numbers of two taxa and the size of one taxa.

It should be noted that although there were significant correlations between the numbers and size of certain of the quantified taxa, and water temperature and salinity changes, this does not necessarily imply a causal relationship. Many other factors might have influenced settlement and growth.

Certain biological factors could also have affected the presence and growth of the attached taxa. Predation could have altered the number of attached individuals (COE, 1932). Flatworms, caprellid amphipods, nudibranchs and fish, which were seen on or in close proximity to the plates, might have eaten and decreased the number of attached individuals.

Competition for food and space by newly attached individuals can limit the number of those individuals and their growth rate (COE, 1932; COE and ALLEN, 1937; MACGINITIE and MACGINITIE, 1968). Competition for food is obviously important in community structure, but our study was not designed to measure it.

BOYD (1972) while working with the fouling organisms at Bodega Harbor, California, found that initial colonization of his substrates was sometimes dominated by only one or two species. This did not happen at Alameda. Competition for space was never very intense except on the 12 month plates, and only a few instances of one species overgrowing another were observed.

As a community develops, and the number of individuals and number of species increases, there begins to be both intra- and interspecific competition for the limited resources. As the competitively successful species become dominant, the less successful will drop out of the community, and the diversity will decrease

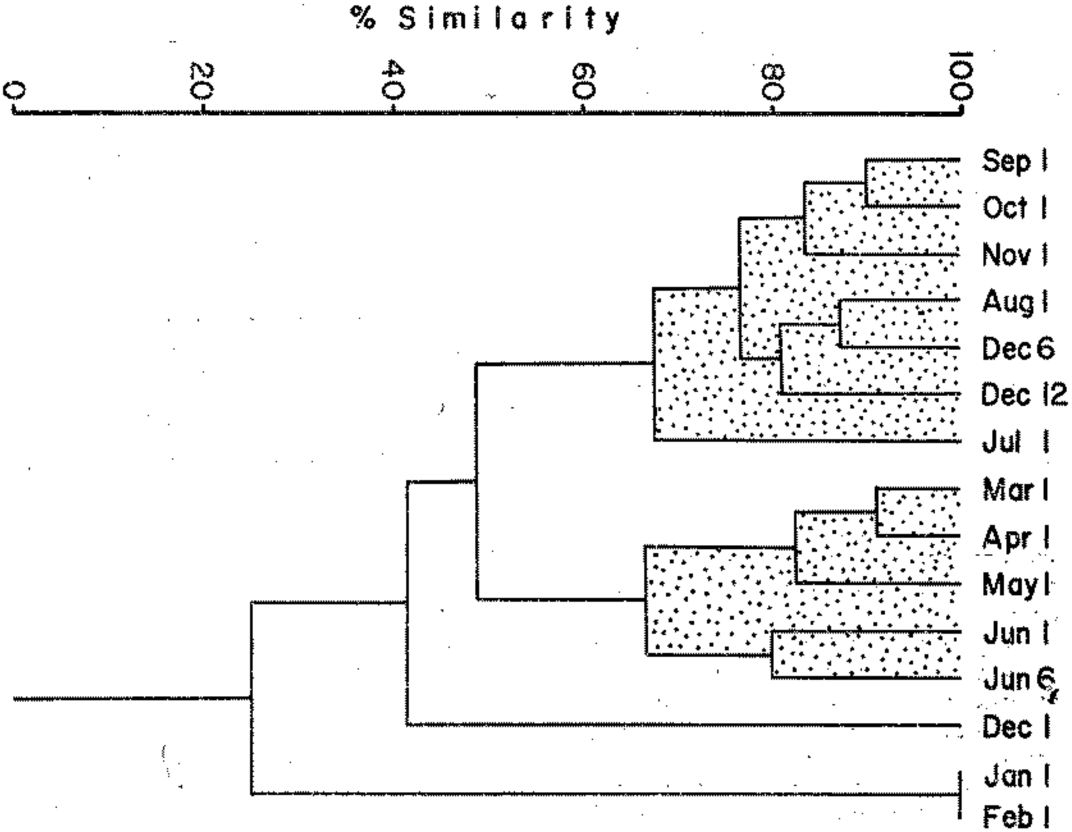

FIG. 8.—Dendrogram portraying similarity between attached taxa on all of the 1, 6 and 12 month sets during 1975. Month refers to the month the plates were examined, and the number designates the months of submergence.

(GRIGG and MARAGOS, 1974). In the present study, competition for space was never intense enough, even on the 12 month plates, to cause a decline in the number of attached species. A comparison of the community on the 12 month plates and the «climax» community on the docks shows that the species richness on the plates might have decreased only slightly if development had continued.

Particularly interesting is a comparison of the present study with one conducted in 1945 by GRAHAM and GAY in the Oakland Estuary. Their observations differed in a few aspects from the present study. They used 16 in^2 (100 cm^2) wooden panels suspended vertically at a constant depth just below the water's surface. It has been found (ALEEM, 1957) that wood and plastic have about the same suitability for attachment and growth of organisms.

Ectocarpus spp., *Vaucheria* spp., *Eteone lighti*, *Eteone californica* and *Tubularia crocea* attached in 1945, but not in the present study. We have found no specimens of the algae or annelids and only one *T. crocea* attached to the docks at Alameda.

Polydora spp., *Corophium* spp. and *Balanus improvisus* were found in both studies, but with much higher numbers in 1945. Bryozoans and ascidians, absent in 1945, now dominate the community at Alameda. *Obelia longissima* and *Ostrea lurida* were also not found in 1945.

These differences in fauna may be due to a number of factors. GRAHAM (personal communication) noted that there was considerable pollution from a sanitary sewer in the area of their study. The decomposition of this sewage might have decreased the dissolved oxygen content in the water to a level which would support only relatively few types of organisms. In 1945, the California State Department of Public Health ordered an end to the discharge of raw sewage into San Francisco Bay waters, and in recent years, extensive improvements in the treatment of industrial and municipal wastes have greatly reduced the amount of pollution in the Bay (San Francisco Bay Conservation and Development Commission, 1969 *a*, 1969 *b*). These improvements are possibly reflected in shifts in faunal abundance, distribution and diversity between the two studies.

Under conditions of moderate pollution there is a tendency for a few tolerant species to survive in unusually high abundance. This has been demonstrated for amphipods (MCNULTY, 1970) and for *Balanus improvisus* (DEAN and HASKIN, 1964; FELICE, 1958). PATRICK, HOLN and WALLACE (1954) found this same trend when working with diatom composition in both polluted and unpolluted river waters. In the Oakland Estuary (GRAHAM and GAY, 1945), the more polluted case, there was a low species richness with a large abundance of each species, while at Alameda Marina, there was less pollution, with high species richness and lower abundance of certain species.

It is also possible that many organisms had not been introduced into the Oakland Estuary by 1945 (see CARLTON, 1975), and thus the differences seen between the two studies are due to the introduction of new species and interspecific competition for the available resources.

SCHEER (1945) working at Newport Harbor, California, and HADERLIE (1974) at Monterey Bay, California, found that the developmental sequence of organisms on experimental panels leading to a «climax» community was not dependent on the time of the year of panel exposure. This was not the case at Alameda. Each taxa, except two, had a seasonal pattern of settlement. Many of the major taxa on the 12 month plates and the docks, were able to colonize plates exposed for only 1 month.

SCHEER (1945) also found that the settlement of ascidians was favored on a surface that was already dominated by bryozoans. At Alameda, all of the ascidians were able to settle on bryozoan-free surfaces.

The Quotient of Similarity values showed a high similarity between some overlapping periods of long and short submergence. Most species attached to the 1 month plates in August were still present on the 12 month plates. Our observations show that neither earlier organisms in the community were essential for the attachment of the later ones nor did organisms disappear as the development of the community continued. Thus, this particular fouling community developed by a seasonal progression and not a true succession. These results correspond with the findings of COE (1932) and COE and ALLEN (1937) at La Jolla, California; KAWAHARA (1962, 1963, 1965) in Japan; BOYD (1972) at Bodega Harbor, California, and others.

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EXPERIMENTS IN SYNTHESIS OF BARNACLE ADHESIVE

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ABSTRACT

Previous investigations of the chemical nature of the adhesive secretion of barnacles showed evidence that the major hardening or curing process of the adhesive is based upon quinone type crosslinking of proteinaceous material. The quinone crosslinking mechanism is studied in view of the major criterions of the adhesives: the wetting properties which are a function of the surface tension, the viscosity parameters, and the hardening process through heteroblock polymerization or crosslinking. Commercially available proteins and model polypeptides are crosslinked with various types of quinones aided by chemical and bio-chemical oxidative agents and catalysts. The progression of the crosslinking is monitored by UV spectrometry since it was shown that this type of crosslinking has a characteristic absorption maximum between 330 and 350 nm dependent on the type of quinone. The feasibility of an adhesive based on proteins and cured by polymerization through quinone type crosslinks was successfully demonstrated. Both the rate of the reaction and the number of generated crosslinks are proportional to the number of lysyl residues. The tertiary protein structure may have high importance in the protein based adhesive system. p-benzoquinone proved to be a usable crosslinking agent. Catechol and other unsubstituted phenols precipitate proteins, therefore, are not practical as adhesive ingredients. Substituted catechols and phenols, such as DOPA in combination with phenolase enzyme produce fast curing and strong adhesives.

INTRODUCTION

The excellent attaching capability of barnacles and mussels and the strength of their attachment has long been recognized. The adverse effects of such attachments prompted a vast search for materials to which these organisms would not adhere, but to date no commercially available nontoxic substance is known to be successful against marine fouling. Barnacles readily attach, for instance, to such slick surfaces as Teflon with such strength that attempted removal breaks their shells rather than the bond of their adhesive. Recent research showed that the adhesive strength of the barnacle adhesive is about an order of magnitude higher than that of the presently used dental adhesives (Despain, DeVries, Luntz and Williams, 1973). Also, the adhesive is extremely resistant to chemicals, attacked only by hot concentrated strong acids or alkalis, or strong oxidizing agents, and has considerable thermal stability (Brown, 1950; Lindner and Dooley, 1972). Along with the underwater application and the curing or hardening time of a few minutes, these characteristics of the adhesives attracted considerable interest in studying these adhesives, with the purpose of development of synthetic adhesives with such desirable properties.

Intensive research aimed at the analysis of the barnacle and mussel adhesive was carried out in several laboratories in the U.S. and abroad in the past decade. In one of these early attempts, LaCombe (1968) indicated acid mucopolysaccharide in both the intra- and extra-cellular secretion, but Saroyan, Lindner, Dooley and Bleile (1969, 1970) showed the proteinaceous nature of the cement, determined

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its amino acid profile, and reported results which already suggested concurrency with the quinone crosslinking mechanism. The subsequent results of HILLMAN and NACE (1970), COOK (1970), CHEUNG and NIGRELLI (1972), WALKER (1972, 1974), BARNES and BLACKSTOCK (1974), CHEUNG, RUGGIERI and NIGRELLI (1974), WALKER and YOUNGSON (1975), and OTNESS and MEDCALF (1972) were in agreement with the proteinaceous nature of the barnacle cement. By histoenzymology, ARVY, LACOMBE and SHIMONY (1969) found alkaline phosphatase activity in the cementing apparatus, and ARVY and LACOMBE (1968) claimed that succinodehydrogenase was demonstrated in young cement glands.

SHIMONY (1972) speculated that the arylsulfatase found in the mantle tissue could be associated with sulphated mucopolysaccharides in the hardening process of the adhesive. WALKER (1971), and SHIMONY and NIGRELLI (1971) on the other hand, found some indication for phenolase activity and phenolic compounds in the larval cement gland and found this evidence to be indicative of a quinone crosslinking mechanism for the larval attachment. Recently, CHEUNG, RUGGIERI and NIGRELLI (1977) questioned the importance of phenolase because using phenolase inhibitors failed to prevent the hardening of the adhesive.

LINDNER and DOOLEY (1973) and LINDNER, DOOLEY and CLAVELL (1972) conducted an intensive histochemical and analytical investigation and compiled evidence which is consistent with the general scheme of a quinone crosslinking of a proteinaceous material as the hardening mechanism of the barnacle adhesive.

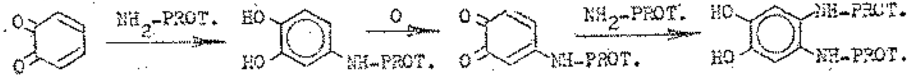
Briefly, this crosslinking mechanism is based upon the spontaneous reaction between a quinone and a nucleophilic reactive group, such as an amino group, of a protein molecule (see formula 1).

The first intermediary is of the monoaminohydroquinone type derivative, which can be reoxidized to quinone to react with another amino compound, thus completing the crosslink. If a protein molecule carries more than one nucleophilic group, infinitely large molecules may be produced through numerous crosslinks.

Our research showed that although p-benzoquinone does form crosslinkages, o-benzoquinone reacts much faster and less selectively with regard to the position of the nucleophilic group (LINDNER, 1971; DOOLEY, 1971; LINDNER, 1973; DOOLEY, 1973). Probably because of such advantages, the o-quinone crosslinkage is the more prevalent in nature. But unlike p-benzoquinone, which is a relatively stable compound and in excess can act as its own oxidizing agent, leading to a reaction with a second nucleophilic group (see formula 2), the o-benoquinone is extremely unstable and quickly decomposes; therefore, it must be produced at the instant of reaction. In nature, it is usually produced from phenolic compounds, such as catechol or its derivatives, through catalytic oxidation by a specific phenolase enzyme (see formula 3).

Also, our research confirmed the possibility of an autocrosslinking mechanism in which the crosslinking quinone is produced from phenolic amino acid residues of the protein, rather than from a separate phenolic crosslinking compound (see formula 4).

We showed that o-benzoquinone prefers this mechanism in which a reaction with only one nucleophilic group is necessary to produce crosslinking between two protein molecules.



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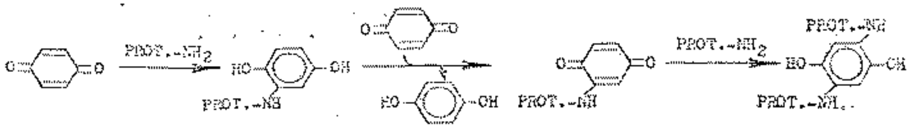

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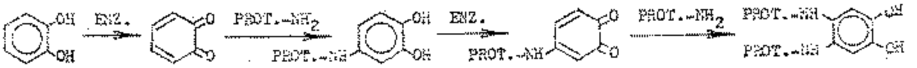

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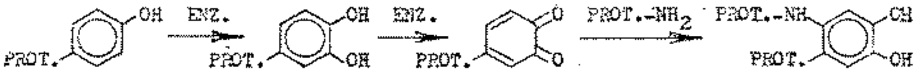

FÓRMULA 4

Indications are that in the case of the barnacle and mussel adhesives, autocrosslinking may take place.

The quinone crosslinking mechanism is one of the most efficient methods of quick polymerization that nature ever developed. The spontaneous reaction propagates a rapid increase in molecular weight without actual physiological (intracellular) involvement and the numerous functional groups carried by the linear polymer (protein) insures dense covalent webbing in the created three dimensional polymer, resulting in unique physical and chemical properties. Such properties as surface tension or wetting characteristics and viscosity of the uncured adhesive, curing time, elasticity, tensile strength, and solubility are dependent upon the size, chemical composition, and structure of the linear polymer, of the crosslinking compound, and of the catalyst. The surface tension of a protein, for example, depends upon the molecular weight or degree of polymerization, the number of hydrophillic groups such as carboxyl or hydroxyl groups on the sidechains, and the secondary structure of the peptide which is determined by the amino acid sequence. Curing time, on the other hand, is regulated by the crosslinking catalyst (enzyme), and dependent upon the crosslinking compound and upon the available crosslinking functional groups which is related to the amino acid composition and sequence. Also, elasticity and tensile strength are related to the secondary and tertiary structure of the peptides and their amino acid composition, mainly the ratio of amino acids with long and short sidechains. By varying these parameters, nature produces various types of quinone crosslinked proteins. As examples, the insect epicuticle is a dark, quite hard, rigid material; the mussel byssus is a brown, elastic thread with high tensile strength; the mussel adhesive disc is lighter in color and retains its softness; the acorn barnacle adhesive is a yellowish-white, rubbery material with good adhesion but relatively little tensile strength; the gooseneck barnacle adhesive, on the other hand, is much darker with high tensile strength. Each of these variations serve a certain specific purpose. The adhesive of the acorn barnacle, for instance, is applied in a very thin layer between the substratum and the large base of the calcareous shell; therefore, tensile strength is not a primary requirement as with the long thin byssuses of the mussel.

Although the basic principles of the relationship between physical and chemical properties and the composition of the ingredient of this type of biopolymer are recognized, the studies were performed on the already hardened, polymerized substances and neither the protein monomer, nor the crosslinking compound, nor the catalyst enzyme has been isolated and identified. It was hoped that, based upon the basic principles, a functional adhesive system could be found without performing much of the time consuming and tedious isolation and sequential analysis work for precise identification of the components.

Commercially available proteins, instead of the actual proteins used by marine invertebratae, were selected to be screened as potential substrates for crosslinking. Most commercial proteins are insufficiently defined as far as amino acid sequence, secondary and tertiary structure is concerned; often, even their molecular weight and amino acid distribution are defined only within broad margins. Nevertheless, some knowledge of the content of the available crosslinking sites in various proteins can be determined or derived from these data. Also, synthetic polypeptides of various amino acid composition and molecular weight were selected to ensure abundance of functional groups for crosslinking. With proper selection of amino acid content, not only the number of crosslinking sites, but the surface tension or wetting characteristics and viscosity of the precursors, and the hardness and tensile strength of the cured product can be controlled.

Very little is known about the natural crosslinking quinones, which are believed to be quite complicated compounds requiring elaborate reaction series before crosslinking can take place. All this is probably required because the quinones and their precursors, the phenols, are toxic to the organism itself. In lieu of these natural compounds, simple quinones and phenols combined with oxidizing agents were selected to be screened as potential crosslinking compounds.

Quinone crosslinking requires relatively strong oxidizing agents as catalysts for propagation of the crosslinking reaction. Even in the oxidized form, the quinone is capable of combining with only one protein molecule because during this reaction it is reduced to a phenolic derivative. In order to make a crosslink by binding another protein molecule, the phenolic derivative has to be reoxidized into a quinone. In nature, the oxidizing agent is an enzyme system which acts effectively and with an exceptionally high reaction rate. No such enzyme system has been isolated to date from marine organisms, but similar enzymes from other sources are available. Besides biological catalysts, chemical oxidizing agents were selected to be screened as potential crosslinking catalysts.

MATERIALS

Table 1 lists the proteins and Table 2 lists the synthetic polypeptides with their specifications and suppliers. Most of the quinone derivatives for potential crosslinking compounds listed in Table 3 were available in the laboratory or were purchased from Aldrich Chemical Co. (Milwaukee, WI). For biochemical crosslinking catalysts, Tyrosinase (mushroom) from Sigma Chemical Co., Catalase (beef liver), and Peroxidase (horseradish) from Miles Laboratories were purchased.

Most common chemical oxidizing agents, such as H_2O_2, $KMnO_4$, $K_2Cr_2O_7$, $HClO_4$ were available off the shelf.

METHODS

Adhesion: For determination of the strength of the model adhesives, an Elcometer Adhe-

TABLE 1

COMMERCIAL PROTEINS USED FOR CROSSLINKING EXPERIMENTS

Protein	*Source*	*Molecular Weight*
Collagen	Calf skin	102,000
Elastin	Bovine neck ligament	
Globulin	Bovine	40,000
Globulin	Pumpkin	40,000
Edestin	Hemp seed	
Gluten	Wheat	
Zein	Corn	
Casein	Bovine	80,000
Albumin	Egg	43,000
Albumin	Bovine	70,000

TABLE 2

COMMERCIAL POLYPEPTIDES USED FOR CROSSLINKING EXPERIMENTS

Polypeptide	*Supplier*	*Molecular Weight*
Poly-L-lysine	Miles Lab.	1,500- 8,000
Poly-L-lysine	"	8,000- 30,000
Poly-L-lysine	"	30,000- 70,000
Poly-L-lysine	"	70,000
Poly-(L-lysine: L-tyrosine) 1:1	"	
Poly-(L-lysine: L-tyrosine) 1:9	"	
Poly-(L-lysine: L-phenylalanine) 1:1	"	
Poly-L-arginine	Sigma Chem. Co.	15,000- 70,000
Poly-L-arginine	"	70,000-150,000
Poly-L-asparagine	"	5,000- 10,000
Poly-L-histidine	"	5,000- 15,000
Poly-L-tyrosine	"	40,000-100,000
Polypep. (random mix. of A.A.)	"	Low viscosity
Polypep. (random mix. of A.A.)	"	High viscosity

sion Tester Model 530/106-I with a measuring range of 0-500 lb/in² was purchased from Zormco (Cleveland, Ohio) (Fig. 1). For determination of adhesion strength, the round, flat surface of an aluminium dolly is coated with the test adhesive and pressed on a flat plate. After the selected curing time, the Adhesion Tester is positioned over the dolly in such a way that the pulling claw can apply force on the dolly (Fig. 2). Tension is applied through a threaded handwheel-spring system and the force required for separation is registered on the scale. During the experiments, the original spring proved to be too strong for recording small changes in adhesive power at the lower ranges, therefore, the tester had to be modified by designing a weaker spring and recalibrating the instrument. Thus, the instrument has an alternative range of 0-10 lb/in².

UV Spectroscopy: A Varian Superscan III (double beam, grating) ultraviolet-visible spectrophotometer was used to detect and measure the rate of the crosslinking reactions. Since the crosslinkages have characteristic absorption between 330 and 350 nm, and most crosslinking compounds have absorption peaks between 250 and 300 nm, the spectra were scanned between 200 and 400 nm. Generally 1 mm pathlength quartz cells were used for measurements. For determination of the rate of reaction, repetitive scanning of the spectra of the reaction mixture was employed with 200 nm per minute scanning speed. Since the solvents and the Sorenson's phosphate buffer used for the dilution of the reaction mixtures are transparent to UV in the scanned region, the spectra were taken against air as reference.

Surface Tension: The surface tension of various protein solutions was determined both by the «capillary rise» method and by a «Cenco Du Nouy Tensiometer». For capillaries, disposable glass micropipettes (0.076 cm I.D.) designed for SMI Micro/Pettor B (Model #1055-B) were used. Both the capillary rise method and the measurements with the Du Nory Tensiometer were performed at 22° C.

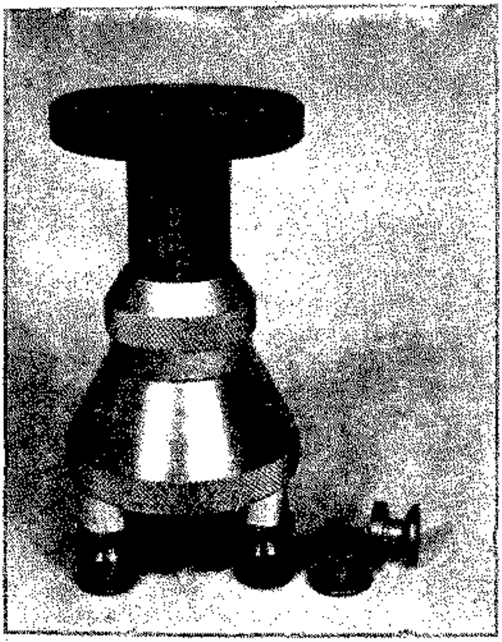

FIG. 1

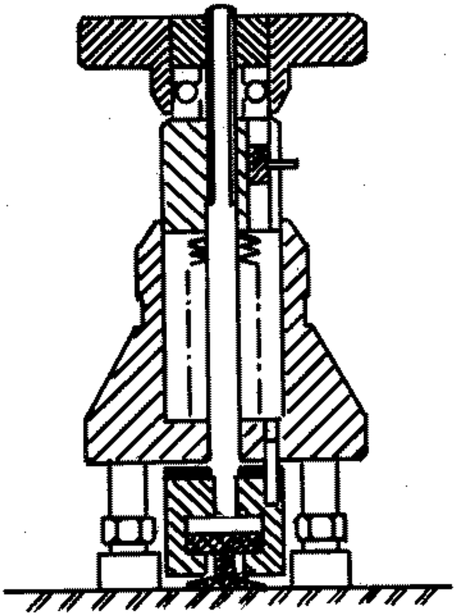

FIG. 2

EXPERIMENTAL

Amino Acid Content: A reasonable degree of crosslinking can be expected only with those proteins which contain a relatively high number of free basic functional groups, primarily amino, imino, and imidazole groups. In quinone crosslinking, the major functional group is the free epsylon amino group of the lysyl residues of the protein chain, while other functional groups of other basic amino acids, such as arginine and histidine participate to a lesser degree. To assess the potential of the model proteins for quinone crosslinking, the amino acid contents of the proteins were obtained from literature and from the suppliers.

Table 4 shows the lysine and the total basic amino acid content of the various proteins, since these amino acids contain functional groups for quinone crosslinking. Zein contains no lysine and only a small amount of other basic amino acids. From among those proteins which show good solubility, gluten and elastin contain only small amounts of lysine, therefore, probably these are not the best candidates for quinone crosslinking. The most promising proteins for crosslinking based on their lysine content in decreasing order are the albumins, globulins, casein, and collagen or gelatin.

Oxidizing Agents: As mentioned previously, the propagation of the quinone crosslinks between protein molecules require oxidizing agents because the quinone is reduced to the hydroquinone form in the first step, binding with the first protein molecule. In order to make the second step, binding with the second protein molecule, it has to be reoxidized to the quinone form. In the case of the orthoquinones, *in situ* oxidation is even more important because these compounds decompose spontaneously.

Since p-quinones are more stable than the o-quinones and actually can act as oxidizing agent to bring the crosslinking reaction to completion, the reaction with p-quinones was first investigated. However, it was soon found that, because of the relative insolubility of the p-quinone in water, the reaction could be performed perhaps through mixing the protein solution with solution of the more soluble hydroquinone and, when curing is needed, oxidized to quinone. Various oxidizing agents

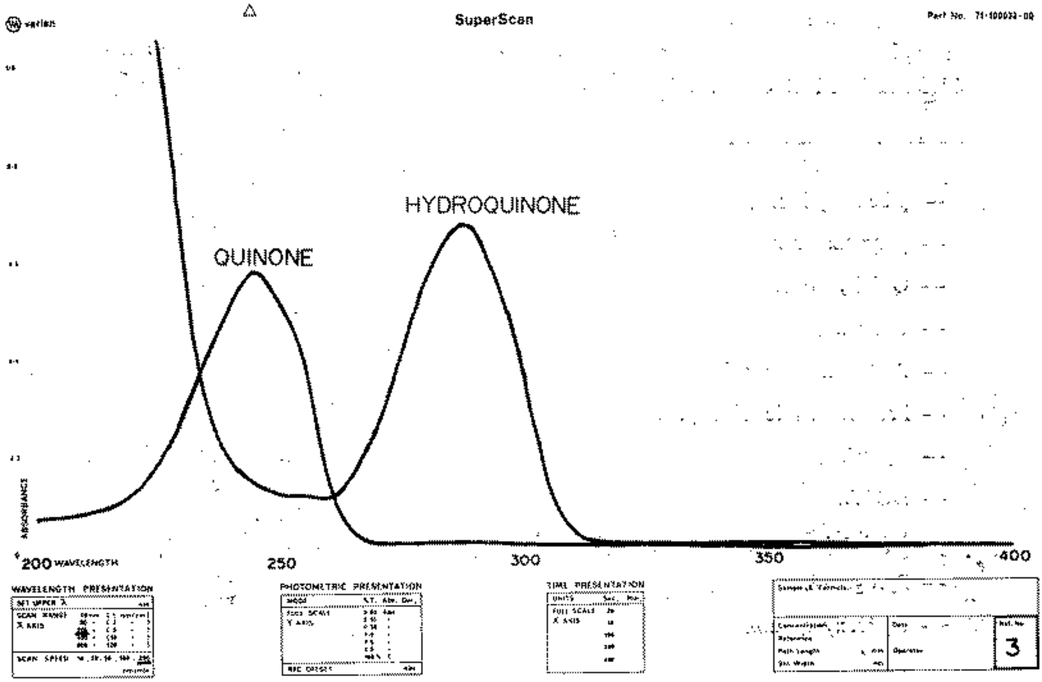

FIG. 3.—UV spectra of p-benzoquinone and p-hydroquinone.

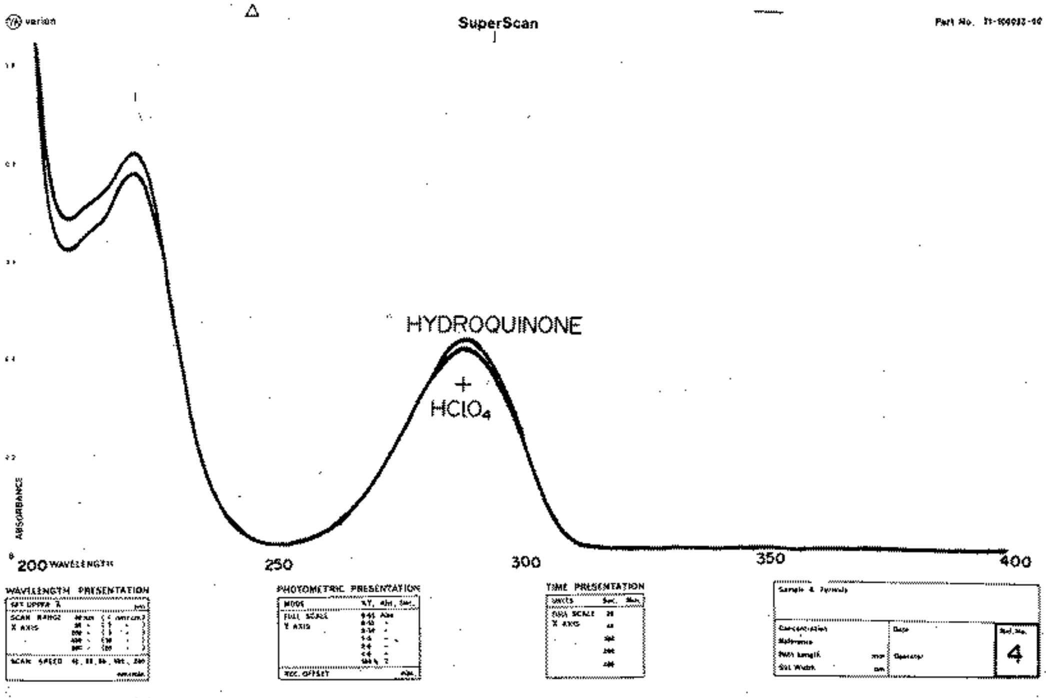

FIG. 4.—Hydroquinone + $HClO_4$.

TABLE 3

CROSSLINKING COMPOUNDS

- p-benzoquinone.
- p-hydroquinone.
- Quinhydrone.
- Catechol.
- Protocatechuic acid.
- Protocatechuic aldehyde.
- Tyrosine.
- DOPA.
- Resorcinol.
- Pyrogallol.
- Hydroxy quinol.
- Phloroglucinol.
- Gallic acid.
- m-digallic acid.

were screened and the reaction was monitored by UV spectrometry, since the hydroquinone and the p-quinone have distinct and different spectra in the UV region. The characteristic absorption of the hydroquinone is at 288 nm while that of the p-quinone is at 245 nm with a shoulder at about 253 nm (Fig. 3). These experiments showed that perchloric acid ($HClO_4$) has no oxidizing effect on hydroquinone (Fig. 4); $K_2Cr_2O_7$ showed only minimal reaction (Fig. 5), and H_2O_2 (Fig. 6) and $KMnO_4$ (Fig. 7) showed relatively strong oxidation of the hydroquinone. Although Tyrosinase has a high specificity toward o-dihydroxyphenols as substrata, it showed marked oxidation of the p-hydroquinone (Fig. 8). The fastest oxidation reaction for hydroquinone, however, was obtained in a 0.25 mM p-hydroquinone solution mixed with traces of catechol (o-hydroquinone) and Tyrosinase (Fig. 9). The significance of this result is that it is supportive evidence to the hypothesis that in nature in some instances the primary crosslinking compound may be a paraquinone, rather than an orthoquinone (DALGLEISH, 1955; DENNELL, 1958 *a*, *b*), which is formed from hydroquinone by the strong oxidizing agent, the o-quinone, which in turn is formed

TABLE 4

LYSINE AND TOTAL BASIC AMINO ACID CONTENT OF PROTEINS

Protein	*% Lysine*	*% Total Basic Amino Acids*
Collagen	4.5	14.1
Elastin	0.5	1.8
Globulin	9.2	25.3
Edestin	2.8	33.7.
Gluten	1.7	11.0
Zein	0.0	5.8
Casein	7.8	14.0
Albumin (egg)	6.5	15.3
Albumin (bovine)	10.9	23.7

from its phenolic precursor by the catalyzing enzyme. Thus, the ortho-phenols may act as secondary catalysts in the system.

Crosslinking Experiments: In our previous works (LINDNER, 1974; LINDNER and DOOLEY, 1972; LINDNER and DOOLEY, 1975; LINDNER and DOOLEY, 1976) the kinetics of the quinone crosslinking reaction mechanism was studied in detail. Since this mechanism involves aromatic compounds in which the conjugated double bond system is being altered, the absorption characteristics of these compounds in the ultraviolet domain was thoroughly investigated. During this study, well-defined absorption regions characteristic to the quinone crosslinks were found. In the case of the p-benzoquinone, a well-defined absorption peak was found around 345 nm, and in the case of o-quinones, a somewhat broader region with lower extinction coefficient appeared with a maximum near 330 nm. These absorption regions proved to be useful for monitoring the quinone crosslinking reactions.

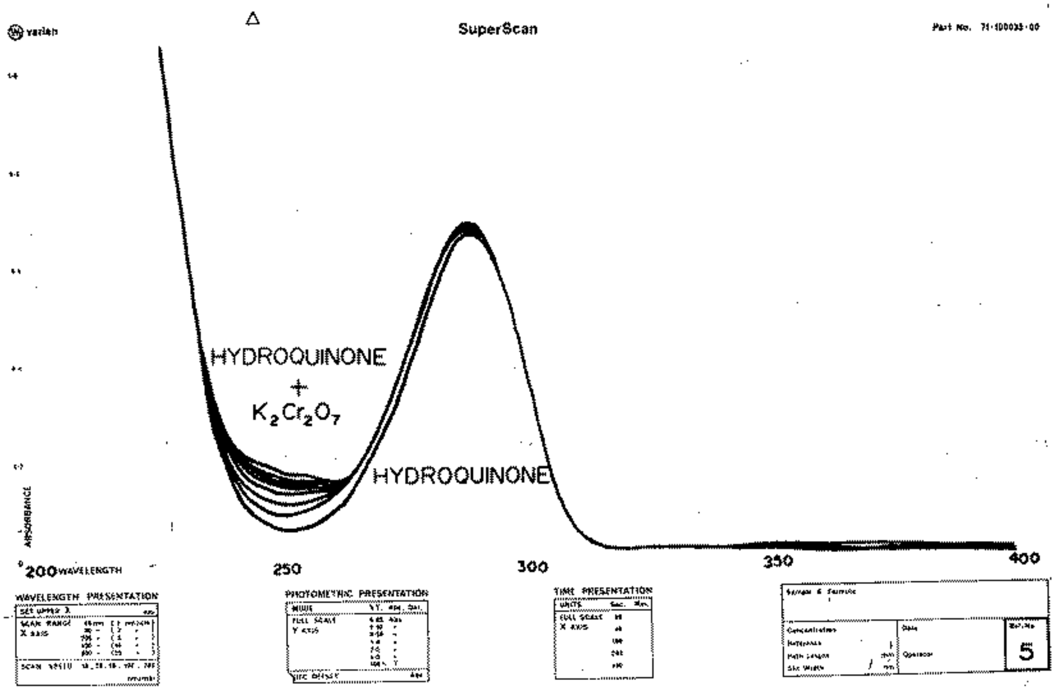

FIG. 5.—Hydroquinone + $K_2Cr_2O_7$.

From the solubility tests and the basic amino acid contents, only albumin, globulin, casein, and collagen or better yet, its degradation product gelatin show promise for successful crosslinking with quinones since their lysine content is 10.9, 9.2, 7.8 and 4.5 % respectively. The other proteins contain only negligible amount of basic amino acids. The high lysine content, however, does not necessarily ensure good crosslinking properties, since the polypeptide chain of the protein can be in such conformation that the functional groups of the basic amino acids are hidden and thus not available for crosslinking.

To test the quinone crosslinking capability of these proteins the reactions were monitored by UV spectroscopy. For comparison, poly-L-lysine (MW 35,000) was also subjected to quinone crosslinking and monitored the same way as the proteins.

For the reaction with p-benzoquinone 0.1 mM protein or polypeptide solution were prepared. Two ml of the polypeptide solutions

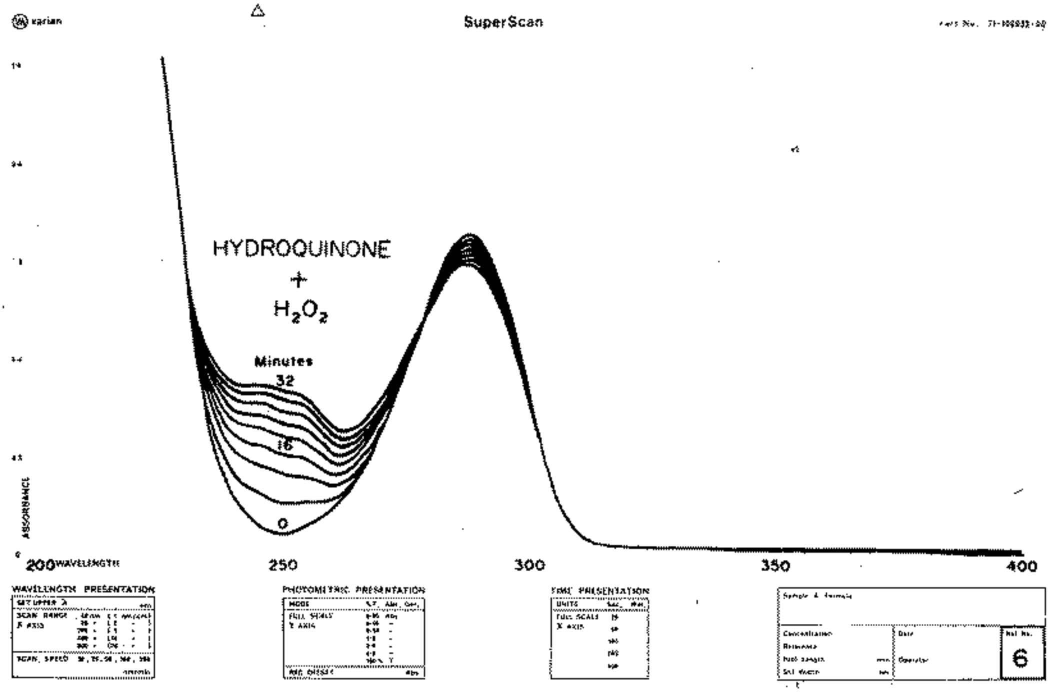

FIG. 6.—Hydroquinone + H_2O_2.

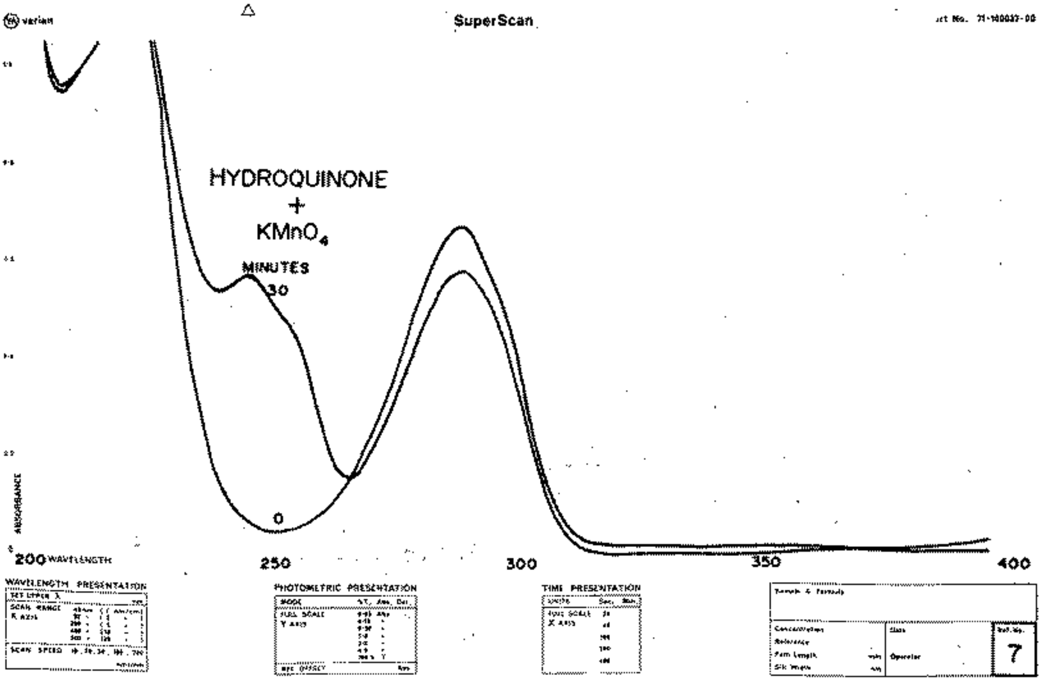

FIG. 7.—Hydroquinone + $KMnO_4$.

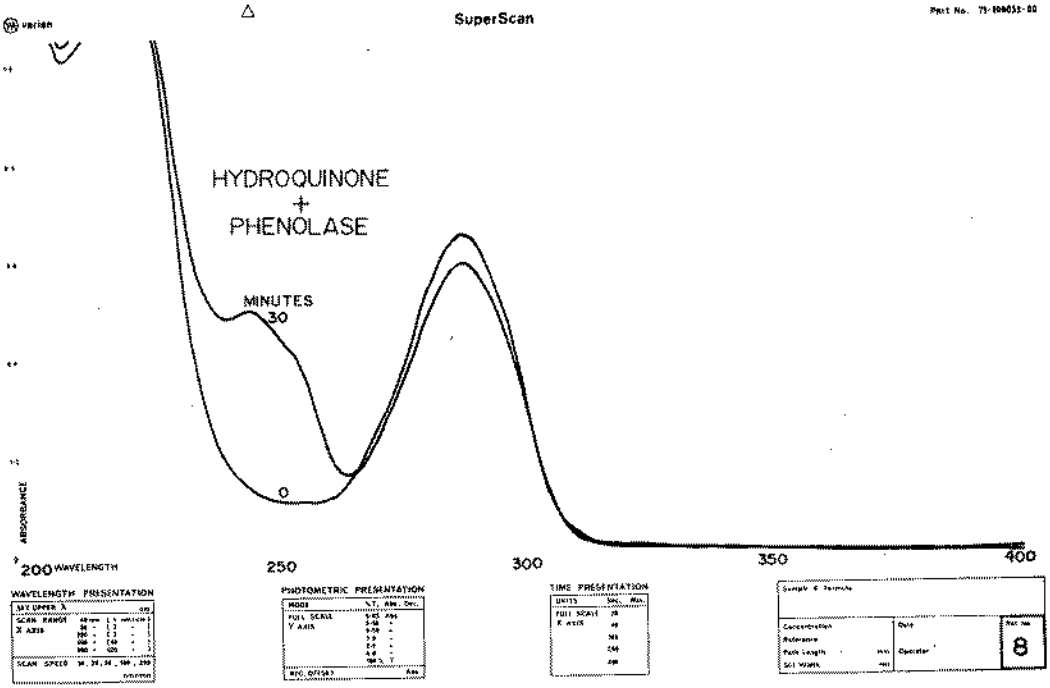

FIG. 8.—Hydroquinone + Tyrosinase.

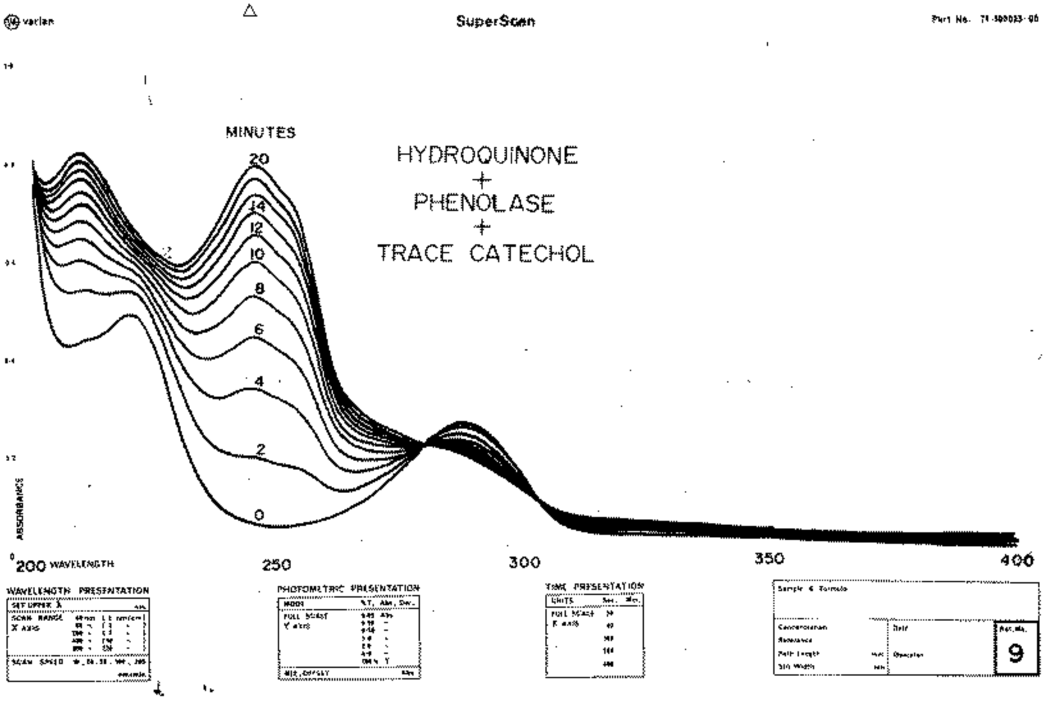

FIG. 9.—Hydroquinone + Catechol + Tyrosinase.

TABLE 5

SURFACE TENSION OF 0.1 M PROTEIN SOLUTIONS

Liquid	*Surface Tension (dyne/cm)*
H_2O	73.1
Gelatin	73.1
Poly-L-lysine	73.1
Albumin	67.4
Globulin	63.7
Casein	54.3
Tergitol NPX (1 % sol)	32.8
Ethanol	22.2

were mixed with three ml of 24 mM p-benzoquinone solution. The rationale behind this ratio was, that there are 240 lysyl residues in the poly-L-lysine with a molecular weight of 35,000. Consequently, for a complete reaction where each lysyl residue would be bound to one quinone, 240 molecules of quinone are needed for one molecule of poly-L-lysine. One molecule of quinone connects two lysyl residues, but two additional molecules of quinone are needed to reoxidize the already reacted and thus reduced quinone in order to complete the reaction. To achieve this theoretical ratio, two parts of 0.1 mM poly-L-lysine is mixed with three parts of 24 mM p-benzoquinone. To make the spectral measurements comparable, this ratio was maintained with the other proteins as well.

From these experiments the spectra indicate that the rate of reaction and the quantity of formed crosslinks are proportional to the lysine content of the polypeptides.

Gelatin, which contains 4.5 % lysine, shows only a trace of increased absorption in the region around 350 nm during the first 16 hours (Fig. 10). This may indicate that only a very few of the lysyl residues are available for crosslinking with quinone. Casein with 7.8 % lysine (Fig. 11), globulin with 9.2 % lysine (Fig. 12) and albumin with 10.9 % lysine (Fig. 13) shows that the reaction progresses during the first 16 hours in proportion with their lysine content. The reaction with poly-L-lysine progresses much faster (Fig. 14) and within 26 minutes the absorption peak at 350 nm reaches about the same intensity as that of albumin or globulin within 16 hours.

The absorption of the o-quinone crosslink proved to be too weak to show any appreciable peak under the selected circumstances. For o-quinone crosslinking, the experimental conditions such as concentrations, reagent ratios, pathlength, etc., were selected similar to those of the p-quinone crosslinking experiments, for comparison. In this case, 2 ml of 0.1 mM polypeptide solutions were mixed with 0.9 ml, 26.5 mM catechol and 0.1 ml phenolase (mushroom tyrosinase) solution containing 500 unit/ml enzyme. The ratio in this case was only one catechol molecule to two lysyl residues since the phenolase enzyme catalyzed the necessary reoxidation reaction. Gelatin (Fig. 15), globulin (Fig. 17) and albumin (Fig. 18) with catechol and phenolase showed no appreciable absorption between 325 and 350 nm. Casein (Figure 16) has a wide absorption region with a maximum at 355 nm even without catechol-enzyme system which may mask absorption generated by o-quinone crosslinks. Only poly-L-lysine (Fig. 19) with enzyme generated o-quinone showed definite absorption in the region near 330 nm, recognized as characteristic of the o-quinone crosslinkage.

Although the crosslinking capability of the proteins with enzyme-generated o-quinones could not be demonstrated to a satisfactory degree, the availability of functional groups of the proteins revealed by the reaction with p-benzoquinone can be extrapolated to the enzyme generated o-quinone system as well.

From the crosslinking experiments it can be concluded that albumin, globulin and casein are good candidates for the quinone crosslinking reaction.

Surface Tension: One of the essential requirements of an adhesive is the good wetting characteristics. A liquid has to have a lower surface tension or surface energy than the solid in order to spontaneously spread on the surface of the solid or wet the surface. The

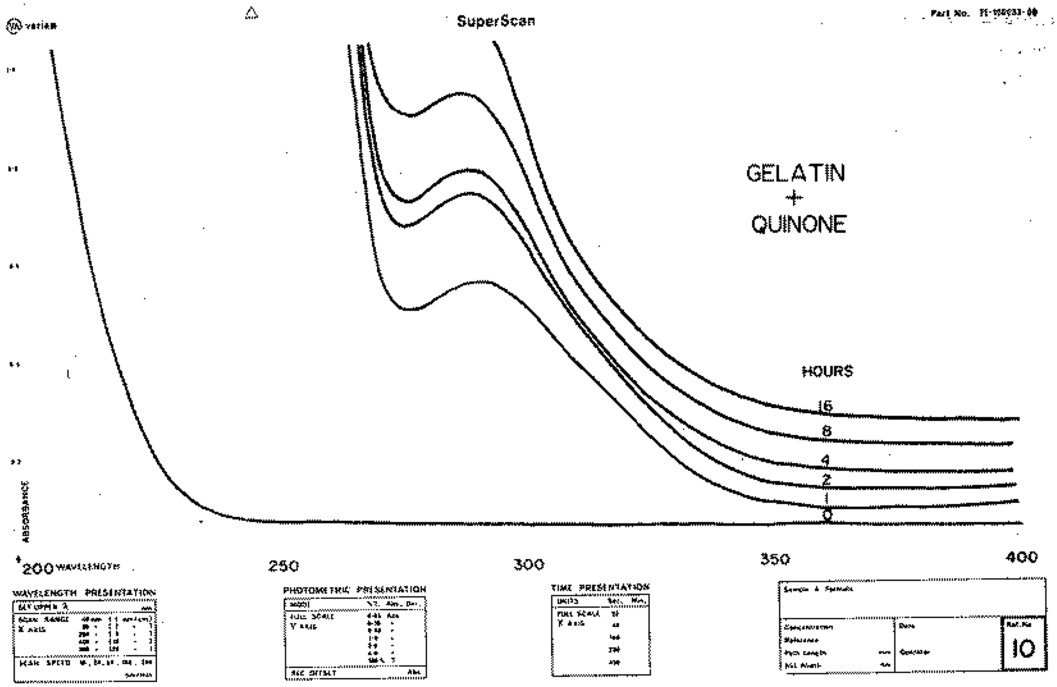

FIG. 10.—Gelatin + Quinone.

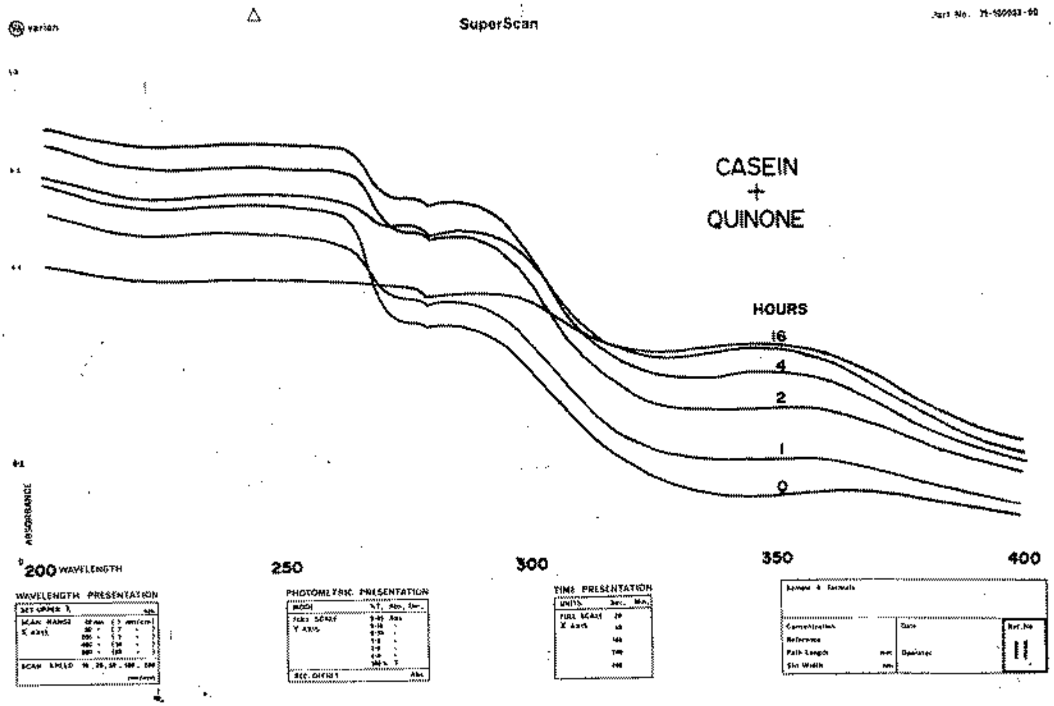

FIG. 11.—Casein + Quinone.

surface tension of a solution is greatly dependent upon the ratio of polar and nonpolar groups of the molecules of the dissolved substance. Table 5 lists the surface tensions of the 0.1 M polypeptide solutions and for comparison, those of some of the solvents and surfactants.

Table 6 indicates that gelatin and poly-L-lysine does not reduce the surface tension of the water (73.1 dyne/cm) and albumin, globulin, and casein reduce the surface tension of water only moderately. For comparison, the surface energy of the hardened barnacle adhesive was determined by equilibrium contact angle method developed by ZISMAN (1964) and resulted a critical surface tension of 12 dyne/cm.

Adhesion Tests: The acceptable adhesive strength for an adhesive was set to 5 psi (0.35 kg/cm²) by the objectives of the project. The various proteins and polypeptides were screened for adhesion strength at various concentrations of aqueous solutions, emulsions and pastes alone and with various crosslinking agents. Since a large number of tests resulted in unacceptably low adhesion strength the following tables show only those tests which have some significance.

Based on the amino-acid composition, crosslinking capability and surface tension, albumin, globulin and casein showed the most promise for an adhesive system based on quinone crosslinking. It was soon learned, however, that favorable wetting characteristics and crosslinking capabilities alone are insuficient for a usable adhesive system. Neither the favored proteins (albumin, globulin and casein) nor those proteins which contain minimum amount of lysine (zein, elastin, gluten and edestin) showed any appreciable adhesive strength in our tests with or without crosslinking agents such as p-benzoquinone, quinhydrone or catechol-phenolase system.

The only commercial protein showing adhesive properies with or without crosslinking agent was gelatin. Gelatin forms a very viscous solution and, probably because of its unique tertiary structure, the water is held within its

TABLE 6

ADHESIVE STRENGTH (kg/cm²) OF 10 % PROTEIN + 1 % P-QUINONE MIXTURES

Protein	*Crosslinking Compound*	MINUTES		
		5	*30*	*120*
Albumin	—	< 0.01	< 0.01	< 0.01
Albumin	p-quinone	< 0.01	< 0.01	< 0.01
Globulin	—	< 0.01	< 0.01	< 0.01
Globulin	p-quinone	< 0.01	< 0.01	< 0.01
Casein	—	< 0.01	< 0.01	0.31
Casein	p-quinone	< 0.01	< 0.01	0.26
Gelatin	—	0.31	0.36	0.80
Gelatin	p-quinone	0.31	0.41	0.78
Polypeptide (high viscosity)	—	< 0.01	< 0.01	0.26
Polypeptide (high viscosity)	p-quinone	< 0.01	< 0.01	0.34
Polypeptide (low viscosity)	—	< 0.01	< 0.01	0.16
Polypeptide (low viscosity)	p-quinone	< 0.01	< 0.01	0.16

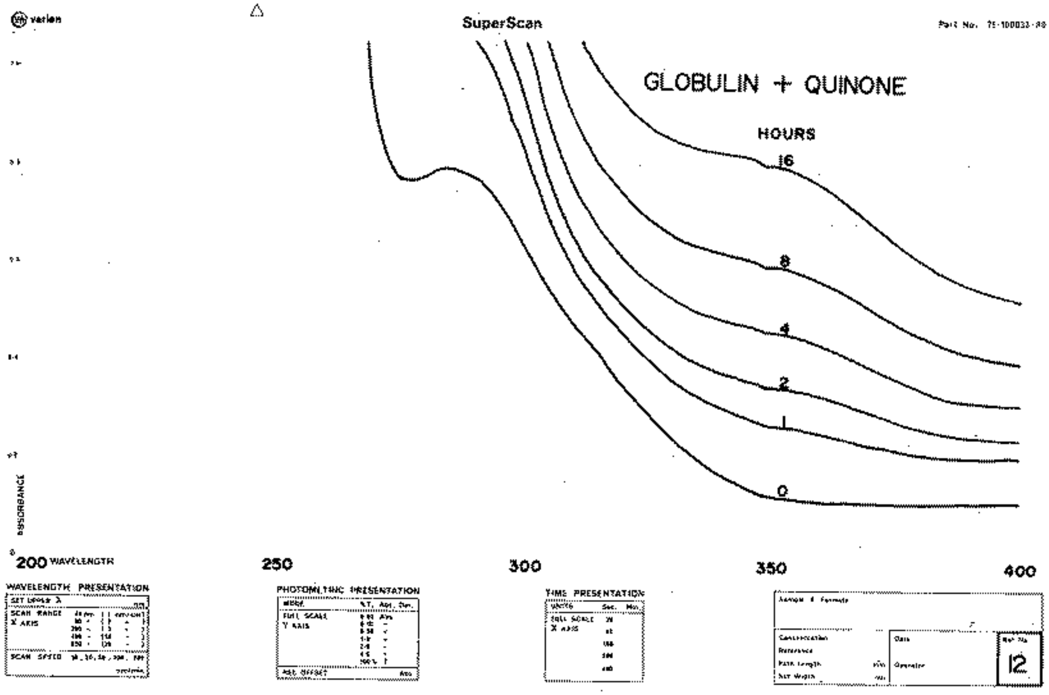

FIG. 12.—Globulin + Quinone.

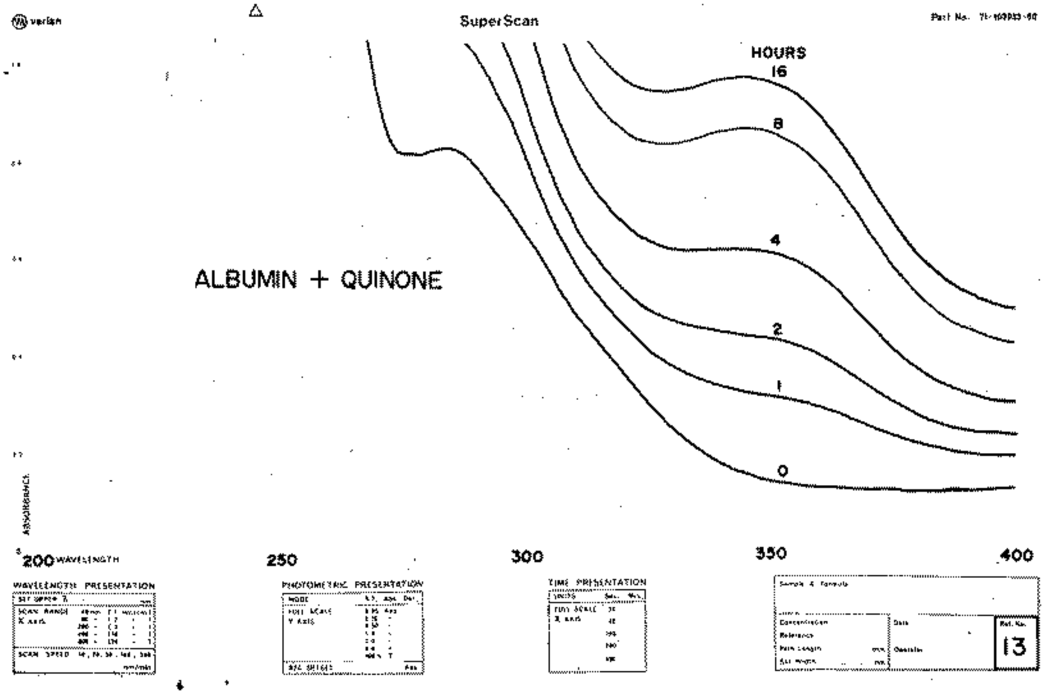

FIG. 13.—Albumin + Quinone.

lattice. These properties may be even more important than the wetting and polymerizing characteristics for adhesion.

This is demonstrated by the results compiled in Table 6. 10 % aqueous solutions of albumin, globulin, casein, gelatin, and high and low viscosity polypeptides are shown from the proteins tested for adhesion both without and with 1 % p-quinone. Albumin and globulin show very little adhesion, casein only after two hours, but gelatin shows fair adhesion already after 5 minutes with some detectable improvement when mixed with quinone. Also, the adhesion of the high viscosity polypeptides is better than that of low viscosity polypeptides. Mixed with p-quinone, the adhesion of the high viscosity polypeptides was improved. Although these experiments were of some value as far as screening for adhesion proper-

TABLE 7

ADHESIVE STRENGTH (kg/cm²) OF 50 % AQUEOUS PASTES OF POLYPEPTIDES AND CROSSLINKING AGENTS

		MINUTES	
Protein	*Crosslinking Agent*	*30*	*120*
Gelatin	—	< .01	.07
Zein	—	< .01	< .01
Albumin	—	< .01	< .01
Globulin	—	< .01	< .01
Casein	—	< .01	< .01
Gluten	—	< .01	< .01
Gelatin	Hydroquinone	< .01	.12
Gelatin	p-quinone	.39	.48
Gelatin	Hydroquinone + p-quinone	.41	.55
Gelatin	Hydroquinone + $KMnO_4$	< .01	< .01
Gelatin	Quinhydrone	.34	.37
Gelatin	p-quinone + quinhydrone	.78	.56
Gelatin	Catechol + phenolase	.17	.20
Globulin	Catechol + phenolase	< .01	< .01
Gluten	Catechol + phenolase	< .01	< .01
Albumin	p-quinone	< .01	< .01
Globulin	p-quinone	< .01	.2
Gluten	p-quinone	< .01	.04
Zein	p-quinone	< .01	< .01
Gelatin + zein	p-quinone	.35	.54
Gelatin + gluten	p-quinone	.29	.41
Gelatin + gluten	p-quinone + quinhydrone	.40	.62

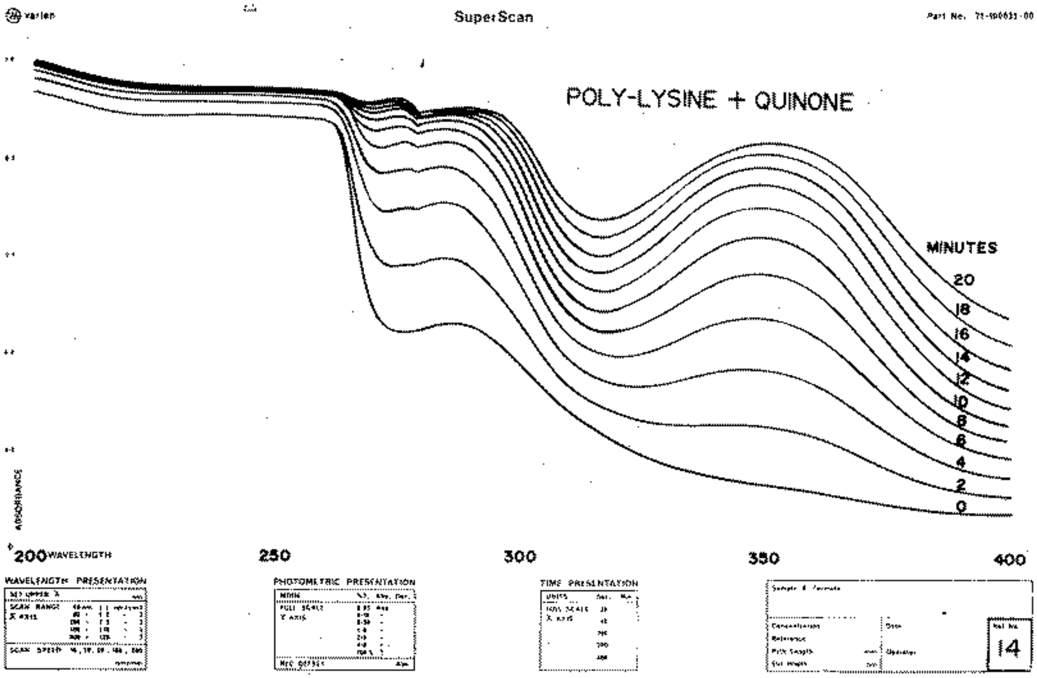

FIG. 14.—Poly-Lysine + Quinone.

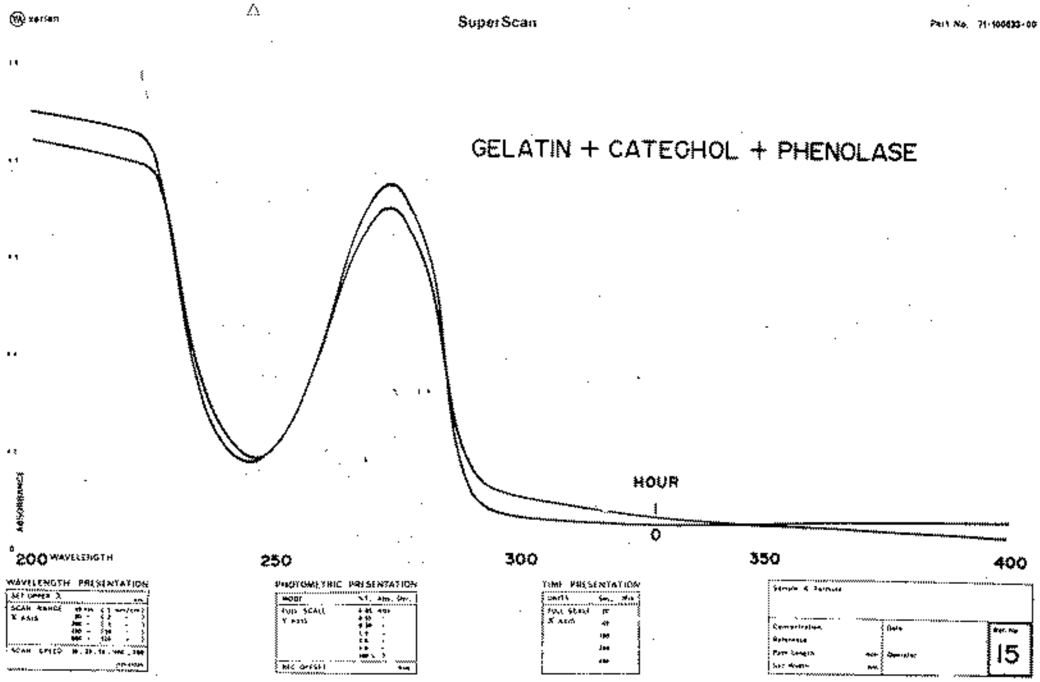

FIG. 15.—Gelatin + Catechol + Tyrosinase.

TABLE 8

ADHESIVE STRENGTH (kg/cm²) OF 30 % GELATIN SOLUTIONS

Protein	Crosslinking Agent	MINUTES 2	5	10	30	60
Gelatin	—	0.22	0.78	0.78	0.75	0.83
Gelatin + ...	3 % p-quinone	1.01	0.93	0.93	0.91	0.72
Gelatin + ...	3 % hydroquinone-p-quinone mix.	0.39	0.82	0.78	0.92	1.02
Gelatin + ...	3 % hydroquinone - $KMnO_4$ mix.	0.14	0.31	0.43	0.45	0.62

ties, it was clear that 10 % solution were too dilute for practical adhesives.

Table 7 shows the adhesion tests of some proteins in a 50 % aqueous emulsion alone and with 10 % of a 50 % aqueous solution or emulsion of the crosslinking agent. In the first part of the table the adhesion of the proteins without crosslinking agent are listed. No tested protein, not even gelatin, showed appreciable adhesion. This can be explained by the low solubility of gelatin in cold water which allowed only the surface of the gelatin granules in the emulsion to be hydrated. Nevertheless, mixed with crosslinking agents,

TABLE 9

ADHESIVE STRENGTH (kg/cm²) OF CROSSLINKED POLYPEPTIDES AT DIFFERENT pHs

		MINUTES			
		pH 4		pH 10	
Protein	Crosslinking Agent	30	120	30	120
Gelatin	p-quinone	.33	.55	.24	.39
Poly-L-lysin	p-quinone	< .01	< .01	< .01	< .01
Gelatin + poly-L-lysin.	p-quinone	.65	.74	< .01	< .01

1:1 ∼ 50 % protein: 50 % crosslinking compound.

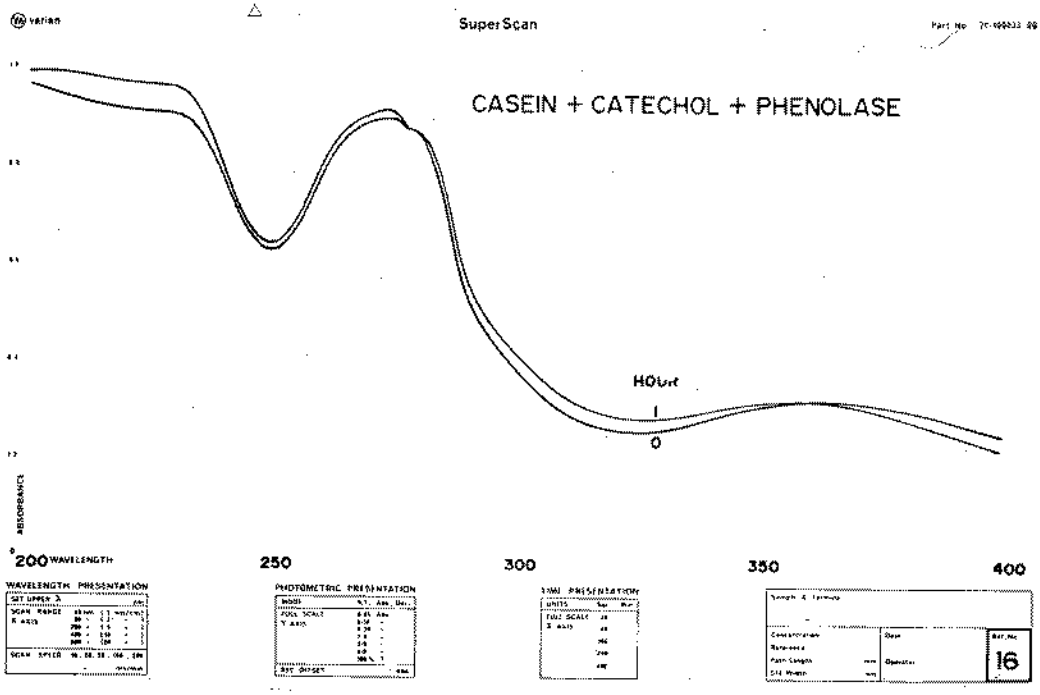

FIG. 16.—Casein + Catechol + Tyrosinase.

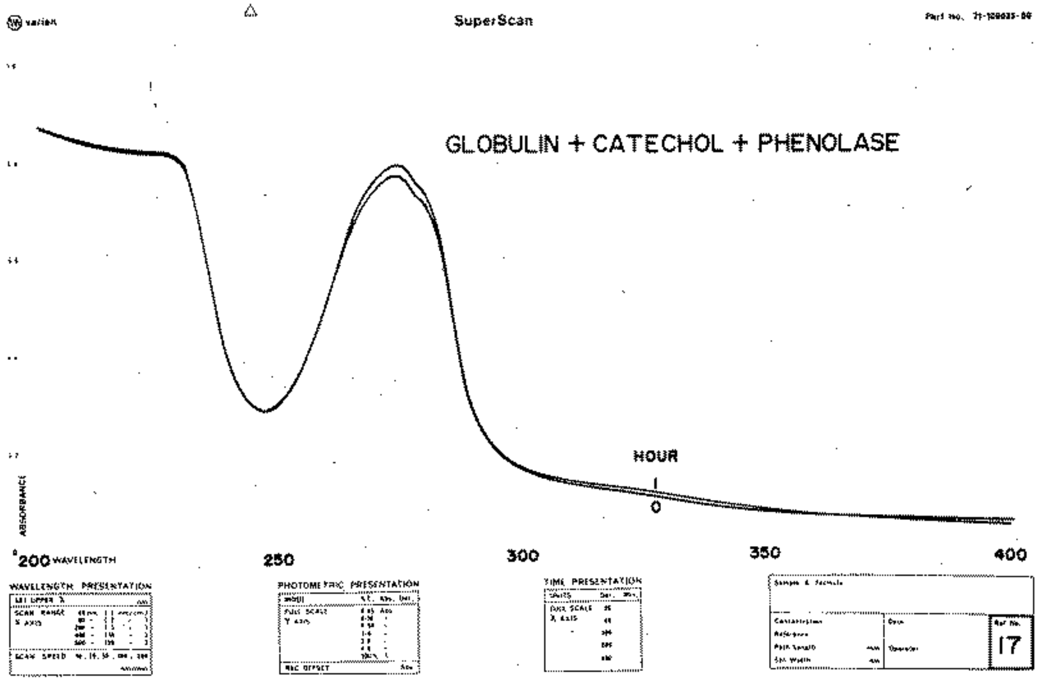

FIG. 17.—Globulin + Catechol + Tyrosinase.

gelatin shows a dramatic increase in adhesion as listed in the second part of the table. Hydroquinone, of course, is not really a crosslinking compound without some oxidative agent, therefore, it did not improve the adhesion of the gelatin. $KMnO_4$, which proved to be one of the better oxidative agents for hydroquinone, did not improve the adhesion at the gelatin-hydroquinone mixture probably because the oxidative character of the permanganate is too strong and it also damages the protein. Among the tested crosslinking agents, the p-quinone-quinhydrone mixture appeared to be the most efficient. Enzyme generated o-quinone (catechol + phenolase) did show some improvement of adhesion of gelatin, but in this series, it did not reach the adhesion improvement of the p-quinone. The adhesion of the other proteins was not improved by crosslinking. To improve consistency of the protein bulk material, 1:1 mixtures of gelatin and other proteins were tested with crosslinking agents. The adhesion of these mixtures was comparable to that of gelatin alone.

Table 8 shows the progression of curing of a 30 % aqueous gelatin solution with and without crosslinking agents. Quinone dramatically reduces the minimum required curing time and maximum adhesion can be achieved within 2 minutes. Quinone-hydroquinone mixture shows less improvement and when $KMnO_4$ was used to oxidize hydroquinone to quinone, a reduction in adhesion was observed probably because of oxidative degradation of the protein backbone. This observation is similar to that shown in Table 7.

Since it was recognized that gelatin is not a good substrate for crosslinking, because of its low lysine content, the adhesion of a polypeptide with maximum lysine content, the poly-lysine (MW 35,000) with p-quinone was tested. Also, since at pH 10 poly-lysine forms an α-helix while under pH 7 it is in random coil, adhesion tests were run at pH 4 and pH 10. Table 9 shows the adhesion of gelatin, poly-L-lysine and their mixtures with p-quinone at these pH-s. Gelatin showed reduced adhesion at pH 10. Poly-L-lysine did not show adhesion, probably because the crosslinking reaction is so rapid that the product coagulates before the adhesion test could be performed. But when diluted with gelatin, the mixture showed excellent adhesion at pH 4 but practically no adhesion at pH 10. Thus it appears that for adhesion a random coil configuration is preferred to the α-helical form of the polylysine.

Catechol and other phenolic compounds tend to coagulate proteins, therefore, the phenolase enzyme was mixed with the bulk protein and to this mixture the phenolic compound was mixed before the adhesion test. In most cases, however, probably because of the rapid crosslinking combined with the phenol's protein denaturizing and precipitating properties, the adhesion tests failed. By

TABLE 10

ADHESIVE STRENGTH (kg/cm²) OF 20 % GELATIN CROSSLINKED WITH O-QUINONE

		MINUTES		
Protein	*Crosslinking Agent*	*10*	*20*	*30*
Gelatin	—	.25	.40	.85
Gelatin + ...	10 % DOPA + phenolase	.70	.60	.78

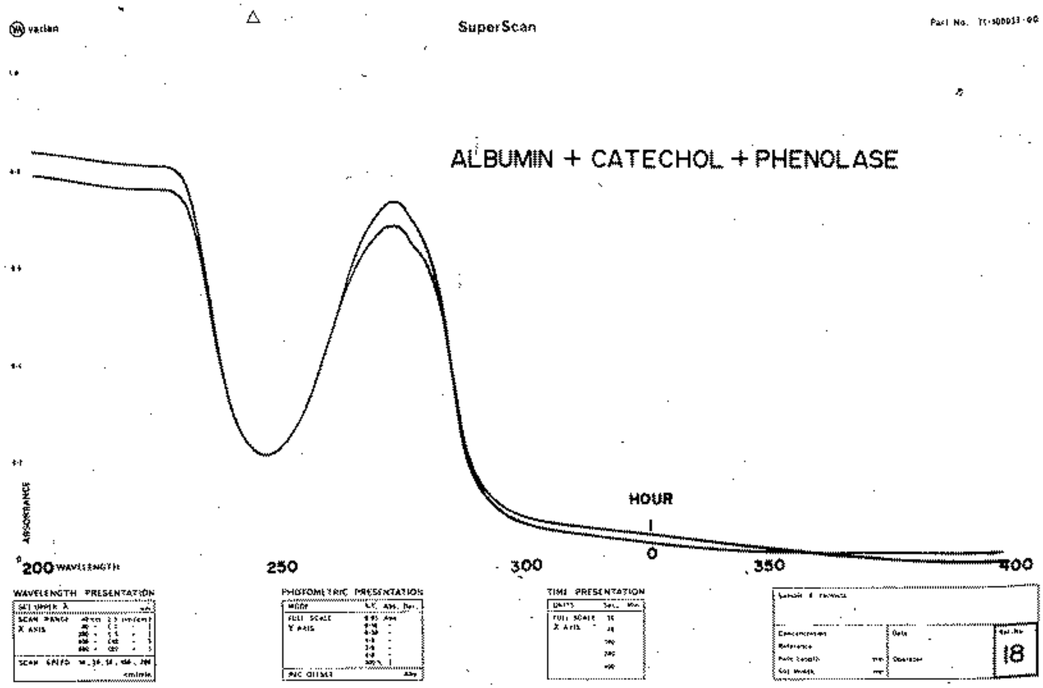

Fig. 18.—Albumin + Catechol + Tyrosinase.

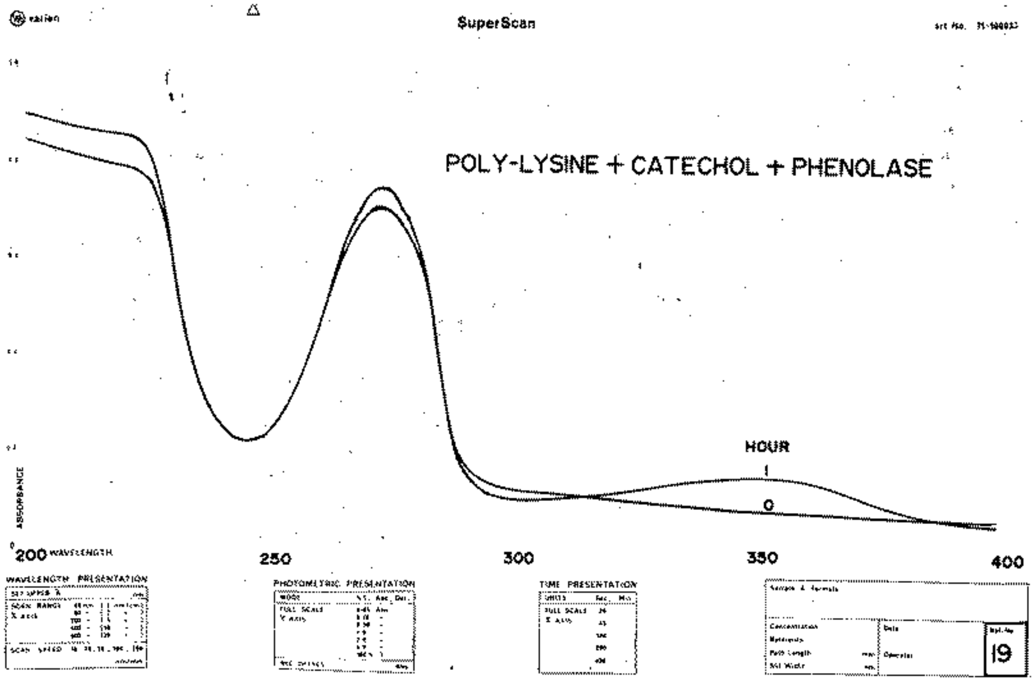

Fig. 19.—Poly-Lysine + Catechol + Tyrosinase.

reducing the concentration of the gelatin solution to 20 % and by using a substituted catechol: the dihydroxy-phenyl-alanine (DOPA), a tyrosine derivative, excellent adhesion was achieved, as shown in Table 10.

CONCLUSION

As described earlier, the adhesive properties of a polymer is a function of a number of parameters related to each other in a complex manner. In order to synthesize and duplicate such an adhesive, especially a biopolymer that cures through the catalytic action of an enzyme, detailed knowledge of the chemical composition of the ingredients is probably essential. Characteristically, enzymes are specific to a certain substrate with distinct functional groups in unique conformations that makes the groups available for the enzyme to act upon and perform the necessary catalytic action. Thus, the chemical composition alone, or the simple knowledge of the reacting functional groups may be insufficient for synthesizing the adhesive. In the case of a protein-based material, it is expected that a knowledge of the amino acid sequence, which determines the tertiary structure of the protein, is essential for the synthesis.

Nevertheless, it was hoped that knowing the basic principals of the reaction and the functional groups involved will be sufficient to select some proteins to be crosslinked resulting in adhesive properties similar to those of the previously studied bioadhesives. This kind of approach, if successful, could make a dramatic shortcut in the lengthy and time consuming path toward the synthesis of the bioadhesive making amino acid sequencing and other complicated analysis procedures unnecessary.

Although the projected objectives could not be achieved, the theoretical and practical feasibility of an adhesive system based on proteins and cured by polymerization through quinone type crosslinks was successfully demonstrated.

Monitoring by UV spectrometry it was shown that both the rate of the crosslinking reaction and the number of generated crosslinks are proportional to the number of lysyl residues present in the polypeptide chain.

It is generally recognized that the primary requirements for an adhesive are good wetting properties resulting from low surface tension, and curing or polymerization to immobilize the position of the adhesive and the adhered surfaces. Our experiments showed that the tertiary protein structure determining viscosity and solvent encapsulation may have an equally high or even higher importance in the protein based adhesive system. Thus gelatin which exhibits good adhesion without crosslinking because of its tertiary structure proved to be a useful bulk protein for adhesives based on quinone crosslinking. It was demonstrated that the curing time of the gelatin can be dramatically reduced and adhesive strength can be improved by quinone crosslinking. Since gelatin itself contains less than 5 % lysyl residues, only minimal crosslinking can be achieved. Mixed with other polypeptides with high lysine content, such as poly-lysine, gelatin results in a fast curing strong adhesive.

p-benzoquinone proved to be a usable crosslinking agent, although it has limitations because of its low solubility in aqueous media. Quinhydrone, an addition compound of quinone and hydroquinone bound by hydrogen bonds seems to improve the curing characteristics of the quinone, probably by preventing polymerization of the quinone.

The more soluble hydroquinone can be mixed with the protein and oxidized by oxidative agents to quinone to produce crosslinks. Although $KMnO_4$ oxidizes hydroquinone readily, it also oxidizes and thus damages the protein resulting in poor adhesion. The fastest and strongest oxidation of hydroquinone can be achieved with phenolase enzyme and traces of catechol, which forms o-quinone and, as a secondary catalyst, promotes the oxidation of hydroquinone.

Catechol and other unsubstituted phenols precipitate proteins, therefore, are not practical as adhesive ingredients. Substituted catechols and phenols, such as DOPA in combination with phenolase enzyme produce fast curing and strong adhesives. In fact, the curing by the phenolase system appears to be so fast that its application becomes dificult. A mixture of proteins which result in a controlled dilution of the functional amino groups may bring the phenolase-substituted catechol-protein system closer to a practical adhesive.

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VARIABILITY AMONG IDENTICAL FOULING PANELS IN PUGET SOUND, WASHINGTON, USA *

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ABSTRACT

The variability of an extensive array of identical fouling panels was investigated over a 1-year period with respect to number of sessile species present, percent cover of major species and similarity between sets of panels of the same age. At any specific time, variability between panels with respect to species numbers was minimal although actual species compositions differed. Percent coverage of panels was slightly more variable. Examining the change in the width of the confidence intervals around these parameters as a function of increasing sample size gives us a basis on which to suggest the minimal number of fouling panels appropriate for observations at this locality. We urge that caution be used in adopting these recommendations at other localities until the factors influencing panel variability are better understood.

1. INTRODUCTION

Despite the extensive fouling literature (see 8 and 16 for references), investigation of the variability between identical panels has been a neglected area of research to date. It is, nonetheless, a necessary one for establishing statistically valid results. This paper documents the variation among a large array of identical fouling panels simultaneously submerged in Puget Sound and periodically examined at intervals during a year's time. A second year of investigation is presently ongoing. Our intent is to characterize the degree to which individual panels differ from one another, and in part suggest what minimum number of panels should be observed to detect general trends.

Although the question of what constitutes an adequate sample size is often posed to statisticians, the answer unfortunately is usually not simple and depends both on the variability of the items studied and the precise questions asked. Here we examine the variability in *a)* number of sessile species attached to panels, *b)* percent cover of major sessile species on panels, and *c)* panel composition, in terms of species identities and abundances.

Since determination of minimum sample size in part depends on the variability of the items under study, we find ourselves involved in a «catch-22» situation; how does one determine the variability of the experiment, in order to determine necessary sample size, without already having conducted the experiment? One answer is to repeat the experiment after pilot surveys are carried out; this procedure assumes that similar events and conditions are repeatable, an assumption which may not always be met for fouling panels (13). Alternatively, one might attempt to over-sample while the study is ongoing, computing variability throughout. We have chosen the latter approach. If more studies of this sort are conducted, we may be able to infer minimum sample size requirements based on parameters

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[1] Figures in parentheses refer to literature references at the end of this paper.

correlated with variability; considerable savings in time and effort, along with statistically valid analyses, should ensue.

Although there have been several decades of fouling research, studies investigating or even commenting on variability of panels *per se* have only recently appeared. Our experiments, designed with this particular goal in mind, attempt to focus attention in this direction.

2. METHODS

In mid-June 1978, 150 identical 20.3 × × 20.3 cm panels, constructed of a textured white formica undersurface glued to a smooth formica upper surface, were independently submerged from floating docks in Phinney Bay, Puget Sound near Bremerton, Washington. The 6 floats from which panels were hung are parallel, 12 m in length; panels were suspended from one side of each dock and exposed to similar illumination. Each panel was suspended horizontally by a 0.64 cm polypropylene hollow-braid rope passing through its center and attached below to an anchor. Panels were separated by a distance of at least 15.2 cm. Bottom depth below panels changed less than 1 m over the width of the study area (33 m), and sediments were similar. Panels towards the shallower end of the site were slightly closer to the surface (subsurface depth = 1 m) and slightly deeper at the opposite end (subsurface depth = 1.3 m).

Only the shaded, undersurface of panels was studied. Previous workers suggested that this surface is the best accumulator of fouling organisms because of reduced sedimentation (6, 14). Accordingly, it is just this surface we consider here.

At localities thought to be representative of the study area, 16 panels were denoted as permanent and these spaced widely apart so as to give an overview of local differences if any existed. At monthly intervals these panels were «non-destructively» observed in running sea water; *i.e.* observations were made on panels and panels were then repositioned for further colonization. Organisms on panels appeared healthy and unharmed by the observation procedure of ca. 3/4 hour's duration.

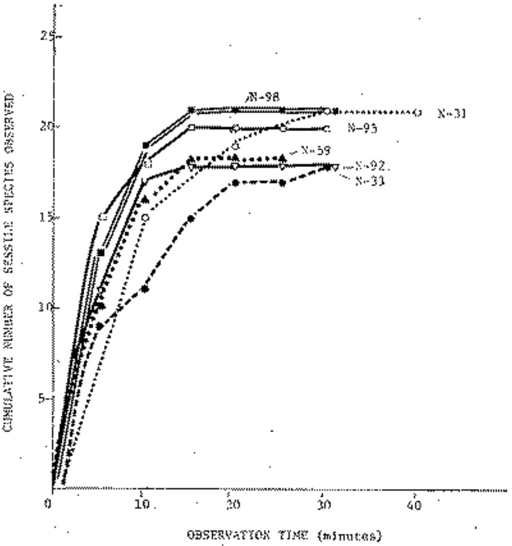


FIG. 1.—Cumulative sessile species counts during individual panel censuses on permanent (N-33) and collected (N-31, 59, 92, 95 and 98) panels.

Among the remaining panels 10 were chosen at random each month, photographed and censused as were the non-destructively observed panels, but after observation they were collected and preserved, *i.e.* «destructively» sampled.

Censuses include a list of all sessile species attached directly to panels, compiled after comprehensive panel examinations. Cumulative number of species vs. observation time generally showed an asymptote in less than 1/2 hour (Fig. 1). In addition to this list of species, percent cover is computed for major panel constituents as in (13). Interactions between sessile species on panels, as well as the presence of motile species, were also recorded.

Salinities and temperatures were noted at several depths in the study site, including those at which the panels rest. Nutrients were measured. These physical and chemical parameters are found in Table 1.

Some of the organisms present on panels in the study area are listed by LAMBERT (5), who also chose this site for fouling investigations. To her list of tunicate species we have added several bryozoans, polychaetes, and additional taxa, to total ca. 70 species. Identifications were based on taxonomic keys for the Puget Sound region, as well as for the Pacific coast in general (4, 9).

TABLE 1

PHYSICAL AND CHEMICAL PARAMETERS MEASURED AT PHINNEY BAY

Date	*Surface temp.* (°C)	*Depth* (*ft*)	S (‰)		PO_4 *		SIO_4 *		NO_3 *		NO_2 *		NH_3 *	
			Sta. 1	*Sta. 2*	*Sta. 1*	*Sta. 2*	*Sta. 1*	*Sta. 2*	*Sta. 1*	*Sta. 2*	*Sta. 1*	*Sta. 2*	*Sta. 1*	*Sta. 2*
9-78	15.5	4	29.7	29.7	1.55	1.83	29.25	27.58	1.07	1.31	0.09	1.31	1.04	4.54
		8	29.7	29.7	1.72	1.60	49.36	35.87	2.05	1.74	0.17	0.11	0.52	0.65
		12	29.7	29.8	1.52	1.65	31.26	36.33	1.77	1.98	0.11	0.12	0.46	2.97
10-78	13-14.5	4	29.9	29.9	1.47	1.79	21.76	40.59	4.99	8.75	0.19	0.36	1.52	1.32
		8	29.9	29.9	1.65	1.80	28.56	39.94	6.67	9.24	0.25	0.36	1.39	1.19
		12	29.9	29.9	1.66	1.79	40.62	37.58	9.75	9.01	0.39	0.33	1.46	1.03
11-78	11.5	4	30.0	30.0	2.29	2.34	50.89	51.49	17.87	18.12	0.53	0.48	3.32	3.29
		8	30.1	30.0	2.37	2.36	51.04	52.25	17.92	18.07	0.49	0.50	3.45	3.52
		12	30.1	30.0	2.36	2.36	51.65	51.04	18.02	18.11	0.50	0.46	3.34	2.44
12-78	9.0	4	29.8	29.8	2.51	2.52	57.74	57.03	23.51	23.51	0.45	0.43	2.93	2.87
		8	29.8	29.8	2.52	2.32	57.73	41.20	23.82	18.50	0.43	0.33	2.85	3.39
		12	29.8	29.8	2.54	2.32	57.21	47.04	23.81	19.81	0.43	0.38	2.97	3.37
1-79	6.5	4	29.9	29.9	2.78	2.91	57.28	59.28	24.71	25.19	0.21	0.29	1.55	1.18
		8	29.9	29.9	2.77	3.87	56.93	60.17	24.33	24.63	0.21	0.23	1.74	2.35
		12	29.9	29.9	2.87	3.18	61.50	57.79	25.76	24.10	0.22	0.22	1.66	1.20
3-79	8.5	4	28.5	28.5	2.11	2.26	23.35	37.69	12.30	16.45	0.12	0.31	1.21	1.95
		8	28.6	28.5	2.20	1.96	35.51	25.56	15.38	11.33	0.18	0.15	1.45	1.19
		12	28.6	28.5	2.09	2.48	33.15	39.60	14.72	17.48	0.20	0.44	1.44	2.13
5-79	12.5-13.0	4	29.1	29.1	1.34	1.51	36.81	37.71	4.58	4.78	0.26	0.25	4.46	4.51
		8	29.2	29.2	1.56	1.32	36.92	37.60	4.73	4.76	0.26	0.22	4.97	3.82
		12	29.1	29.2	1.35	1.33	37.49	38.06	4.76	4.75	0.25	0.24	4.30	4.04

* µM.

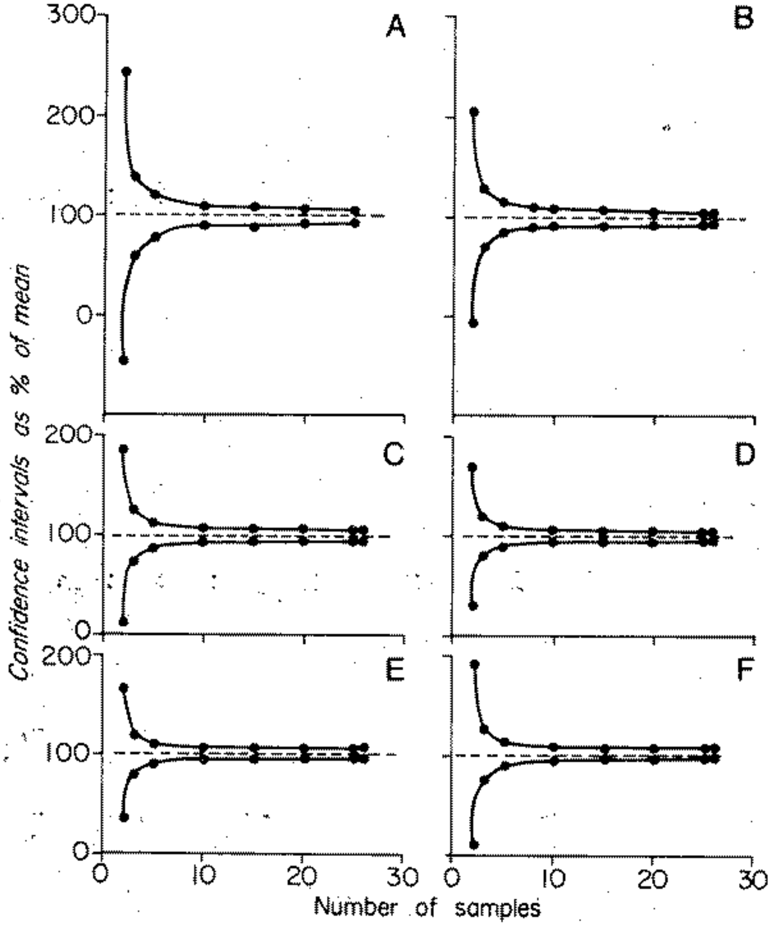


FIG. 2.—The upper and lower 95 % confidence limits (expressed as percentage of the mean) plotted versus sample size (number of panels). The data represent mean number of sessile species on panels and are based on the variance observed for 26 panels on the following dates after panel submergence: A) Week 3; B) Week 7; C) Week 11; D) Week 16; E) Meek 20 and F) Week 24.

3. RESULTS

Our Phinney Bay locality is well-known for its abundance of tunicates, both solitary and colonial (5). Although tunicates predominate on panels during the first year, a variety of sessile fouling organisms are also present. The results reported below refer to those sessile species ca. 0.5 mm and larger attached directly to panels.

During the course of our experiments minimal water temperatures of 6.5° C and maximal temperatures of 15.5° C were recorded and this range corresponds to that surface temperature range reported a decade earlier at the same locality (5). Although rainfall in the Puget Sound region is seasonal, salinities at our site were fairly constant, indicating a good flushing rate in the Bay. Currents of up to 1.5 knots can occur.

Variability in species counts: The mean number of attached sessile species per panel, and the standard error, were computed in each series for every observation date. The 95 % confidence limits for increasingly large sample sizes are shown in Figures 2 and 3. Testing the data for deviations from normality by the Kolmogorov-Smirnoff test (12) showed

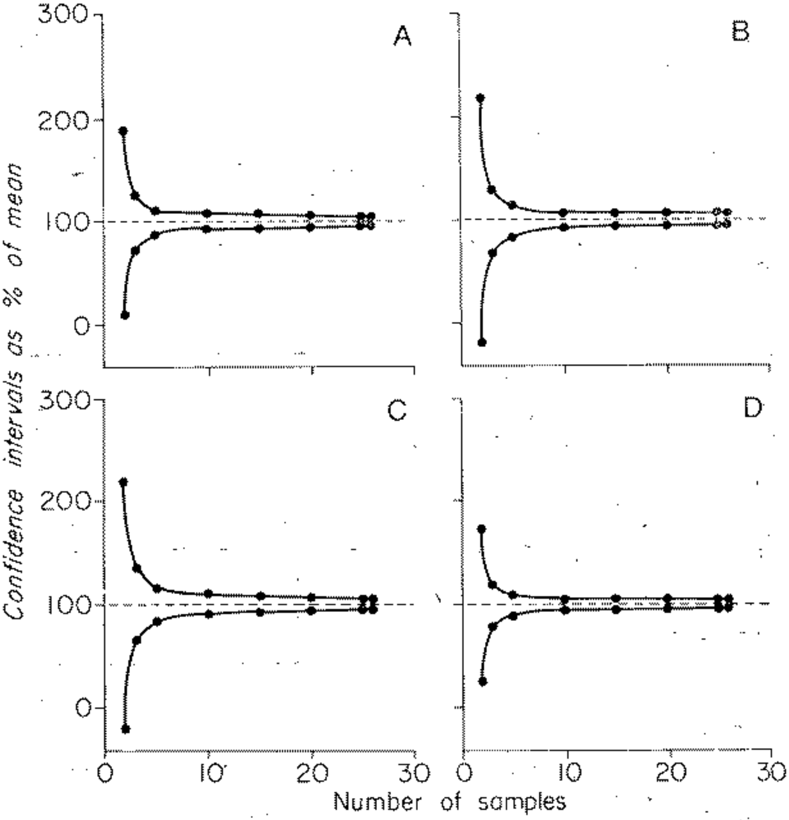


FIG. 3.—Confidence limits for mean number of sessile species as in Figure 2 for A) Week 30; B) Week 39 and C) Week 48; and D) for mean percent cover on panels during Week 48.

that assumptions of normality were not violated ($P < 0.05$), and these and subsequent data were not transformed. We computed «trumpet» diagrams (2, 3), which indicate the width of the confidence intervals around the mean as a percentage of the mean, for successive weeks (Figs. 2 and 3). These confidence intervals generally span 10 % on either side of the mean, and are only slightly reduced by increasing sample size beyond samples of 5-10. Since variability in species counts between panels is not substantial, our results suggest that there is decreasing benefit in observing increasingly large sample sizes.

Variability in percent cover: Using a random point method to calculate percent cover, 100 random points are plotted on plexiglass sheets prior to each census, and generated anew for each subsequent observation on the same panel. Sheets are placed over panels and species below points recorded. By this method panel coverage can be estimated for major space occupiers to within 5 % (14). We calculated percent cover for each panel and computed means and standard errors based on the 26 panels examined at each date. Trumpet diagrams, shown in Figures 4 and 5, indicate the 95 % confidence intervals around the mean and their change with increasing sample size over the dates examined. Again, confidence intervals are generally reduced with increased sample size as the first 5-10 samples are observed, and thereafter the width of the interval is not appreciably changed by increasing sample size further. Except during the first observation period when confidence intervals are much wider, intervals spanning 10 % on either side of the mean are typical, and these

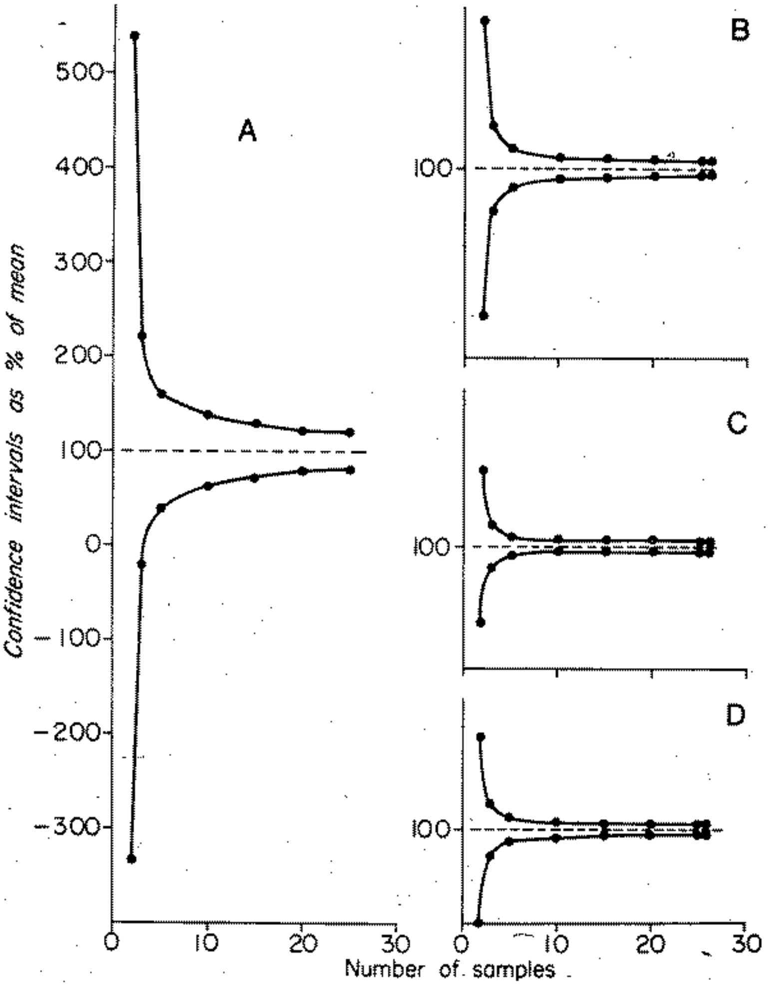


Fig. 4.—The upper and lower 95 % confidence limits (expressed as percentage of the mean) plotted versus sample size (number of panels). The data represent mean percent coverage of panels and are based on the variance observed for 26 panels on the following dates after submergence A) Week 3; B) Week 7; C) Week 11 and D) Week 16.

generally decrease little with increased sample size beyond 10 samples.

Similarity of panels: Until this point we have considered variability in terms of numerical values alone, ignoring the actual species composition on panels. We next consider variation in terms of species identities and their proportions on individual panels. To do so, we can compute the similarity of sets of panels at each time interval using the Bray-Curtis similarity index (15):

$$I_a = 1 - 0.5\ \Sigma\ |a\text{-}b| = \Sigma\ \min\ (a,\ b)$$

where a and b are the fractional proportions of the species present. Empty space on panels is incorporated into these calculations equivalent to an additional species. Values of 0 reflect minimal similarity while values of 1 reflect identical panels. Analyses of our 16 non-destructively sampled panels through time show the following trends. During the first observation period there is considerable similarity (values of 0.9 or higher in nearly all comparisons) between panel sets, but this decreases with time, until a mean value of

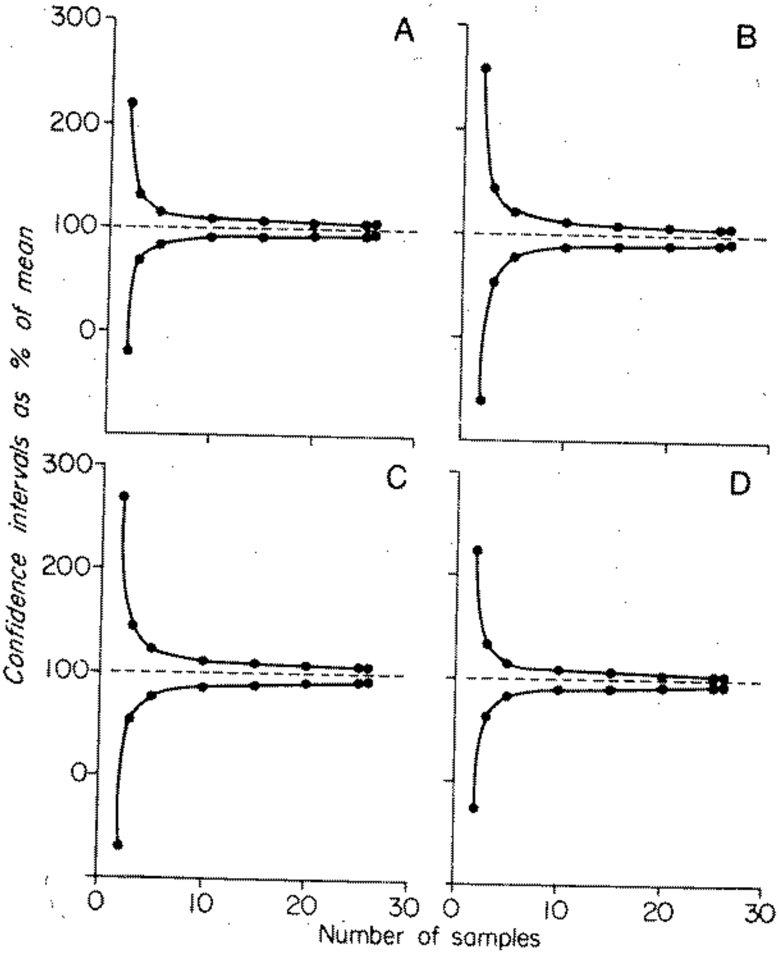


FIG. 5.—Confidence limits for mean percent coverage of panels as in Figure 4 for dates: A) Week 20; B) Week 24; C) Week 30 and D) Week 39.

ca. 0.5 is approached. Especially during the first census period, empty space on panels is high and this probably accounts for the high similarity values initially observed. However, for the 6 major colonizing species detectable by point sampling during the initial observation period, colonization does appear to be similar between panels.

Similarity values were clustered to produce the dendrograms shown in Figures 6-9 for all census periods after the first. The ordinate in each graph represents a distance mesure (1-similarity). In the 7th week (Fig. 6), many panels cluster together by the 60 % similarity level, and two additional smal cluster groups occur as well. In following weeks, the number of cluster groups at this level increases to ca. 6 and fluctuates around this number. We intend to examine in detail the biological events leading to these cluster groups at a later day, but would like to point out here that the relative abundance of a solitary tunicate species, *Corella willmeriana,* markedly affects the clustering pattern of the panels at each observation date.

4. DISCUSSION

For the tunicate-dominated community in Phinney Bay, our studies suggest that variability in species numbers or total percent cover among panels is not substantial during the

	N-02	N-08	N-24	N-33	N-43	N-50	N-58	N-63	N-75	N-81	N-87	N-104	N-117	N-123	N-135	N-147
N-02	-	0,76	0.52	0.31	0.51	0.80	0.69	0.34	0.59	0.70	0.74	0.41	0.49	0.57	0.72	0.53
N-08	0.64	-	0.45	0.25	0.47	0.83	0.90	0.32	0.51	0.59	0.64	0.32	0.43	0.53	0.64	0.43
N-24	0.76	0.66	-	0.56	0.83	0.56	0.35	0.54	0.82	0.62	0.68	0.85	0.71	0.63	0.63	0.70
N-33	0.56	0.49	0.76	-	0.47	0.35	0.23	0.21	0.65	0.29	0.29	0.68	0.34	0.22	0.27	0.30
N-43	0.76	0.65	0.77	0.60	-	0.56	0.40	0.65	0.74	0.63	0.70	0.75	0.83	0.72	0.64	0.78
N-50	0.66	0.80	0.82	0.70	0.75	-	0.76	0.36	0.62	0.60	0.66	0.44	0.50	0.54	0.66	0.50
N-58	0.54	0.85	0.64	0.51	0.66	0.73	-	0.32	0.43	0.53	0.66	0.25	0.38	0.45	0.56	0.36
N-63	0.76	0.70	0.81	0.63	0.85	0.81	0.68	-	0.41	0.50	0.57	0.45	0.81	0.70	0.64	0.78
N-75	0.79	0.73	0.81	0.64	0.88	0.85	0.74	0.88	-	0.60	0.60	0.80	0.58	0.50	0.56	0.57
N-81	0.71	0.84	0.82	0.60	0.78	0.83	0.81	0.80	0.86	-	0.82	0.52	0.62	0.68	0.80	0.66
N-87	0.60	0.77	0.72	0.59	0.71	0.76	0.86	0.73	0.78	0.86	-	0.59	0.67	0.83	0.89	0.73
N-104	0.87	0.63	0.73	0.54	0.67	0.66	0.53	0.73	0.72	0.68	0.57	-	0.58	0.53	0.51	0.60
N-117	0.66	0.75	0.77	0.62	0.73	0.78	0.72	0.77	0.80	0.88	0.84	0.63	-	0.78	0.62	0.90
N-123	0.78	0.67	0.80	0.62	0.84	0.77	0.66	0.84	0.86	0.81	0.76	0.70	0.80	-	0.79	0.68
N-135	0.62	0.77	0.73	0.63	0.67	0.77	0.85	0.72	0.76	0.82	0.93	0.58	0.81	0.75	-	0.69
N-147	0.75	0.80	0.80	0.61	0.84	0.82	0.79	0.85	0.93	0.92	0.84	0.72	0.86	0.82	0.81	-

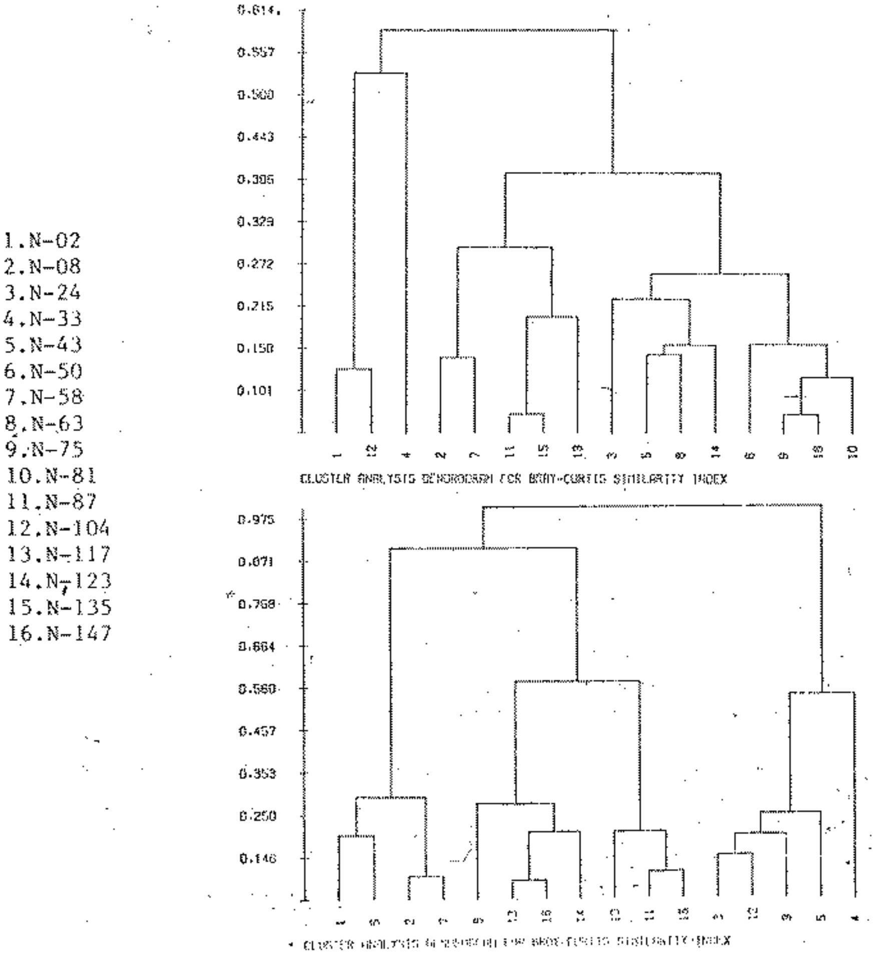
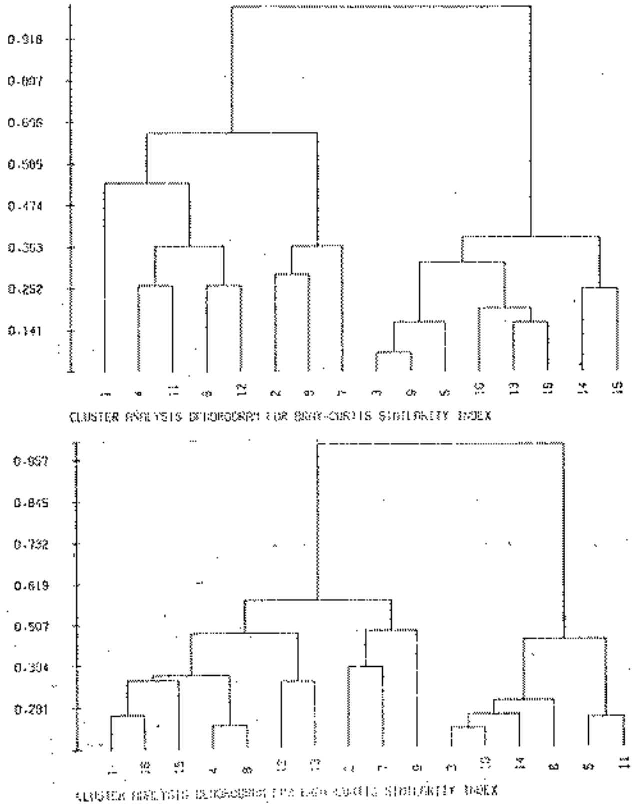


FIG. 6.—Matrix of similarity values for panels at week 1 (lower left) and week 11 (upper right). Corresponding cluster diagrams for week 7 (TOP) and week 11 (BOTTOM). Abscissa in diagrams shows each of 16 permanent panels; ordinate is a distance measure (1-similarity).

	N-02	N-08	N-24	N-33	N-43	N-50	N-58	N-63	N-75	N-81	N-87	N-104	N-117	N-123	N-135	N-147
N-02	-	0.61	0.33	0.63	0.39	0.38	0.60	0.66	0.52	0.35	0.20	0.56	0.45	0.39	0.67	0.74
N-08	0.63	-	0.40	0.61	0.35	0.55	0.61	0.67	0.47	0.44	0.28	0.59	0.51	0.49	0.60	0.60
N-24	0.47	0.39	-	0.49	0.73	0.73	0.24	0.48	0.34	0.78	0.62	0.51	0.59	0.77	0.46	0.54
N-33	0.66	0.64	0.68	-	0.31	0.53	0.50	0.77	0.45	0.47	0.25	0.59	0.61	0.53	0.68	0.71
N-43	0.36	0.27	0.82	0.56	-	0.64	0.18	0.36	0.25	0.76	0.75	0.37	0.51	0.65	0.34	0.39
N-50	0.42	0.48	0.63	0.69	0.67	-	0.42	0.60	0.44	0.72	0.54	0.56	0.57	0.71	0.42	0.56
N-58	0.39	0.70	0.35	0.53	0.22	0.52	-	0.63	0.59	0.23	0.11	0.47	0.41	0.25	0.54	0.47
N-63	0.58	0.71	0.59	0.67	0.51	0.59	0.60	-	0.62	0.46	0.26	0.69	0.61	0.46	0.65	0.71
N-75	0.42	0.35	0.91	0.63	0.89	0.67	0.30	0.55	-	0.26	0.09	0.43	0.50	0.41	0.61	0.51
N-81	0.45	0.35	0.79	0.54	0.69	0.45	0.29	0.57	0.71	-	0.72	0.46	0.56	0.73	0.40	0.53
N-87	0.58	0.45	0.64	0.74	0.60	0.61	0.37	0.53	0.65	0.54	-	0.32	0.37	0.55	0.21	0.31
N-104	0.53	0.40	0.64	0.71	0.62	0.74	0.34	0.54	0.65	0.50	0.68	-	0.64	0.46	0.54	0.63
N-117	0.47	0.43	0.85	0.60	0.76	0.56	0.35	0.61	0.81	0.77	0.59	0.57	-	0.66	0.63	0.65
N-123	0.39	0.25	0.74	0.48	0.72	0.46	0.19	0.45	0.75	0.69	0.49	0.48	0.72	-	0.48	0.54
N-135	0.47	0.45	0.75	0.54	0.63	0.40	0.36	0.61	0.67	0.64	0.50	0.43	0.53	0.75	-	0.66
N-147	0.49	0.51	0.81	0.60	0.71	0.58	0.46	0.72	0.78	0.74	0.61	0.51	0.84	0.66	0.73	-



1. N-02
2. N-08
3. N-24
4. N-33
5. N-43
6. N-50
7. N-58
8. N-63
9. N-75
10. N-81
11. N-87
12. N-104
13. N-117
14. N-123
15. N-135
16. N-147

FIG. 7.—Matrix of similarity values for panels at week 16 (lower left) and week 20 (upper right). Corresponding cluster diagrams for week 16 (TOP) and week 20 (BOTTOM). Abscissa in diagrams shows each of 16 permanent panels; ordinate is a distance measure (1-similarity).

	N-02	N-08	N-24	N-33	N-43	N-50	N-58	N-63	N-75	N-81	N-87	N-104	N-117	N-123	N-135	N-147
N-02	–	0,64	0,56	0.60	0.46	0.52	0.55	0.50	0,40	0.54	0,47	0.45	0.59	0.52	0.61	0.58
N-08	0.70	–	0.53	0.70	0.52	0.68	0.65	0.54	0.42	0.48	0.53	0.37	0.54	0.60	0.55	0.61
N-24	0.41	0.32	–	0.65	0.66	0.67	0.62	0.62	0.50	0.72	0.64	0.47	0.77	0.75	0.70	0.76
N-33	0.73	0.75	0.39	–	0.58	0.74	0.69	0.54	0.43	0.59	0.51	0.65	0.64	0.66	0.73	0.72
N-43	0.34	0.26	0.79	0.25	–	0.44	0.52	0.51	0.39	0.60	0.44	0.38	0.68	0.79	0.53	0.64
N-50	0.71	0.62	0.44	0.69	0.38	–	0.70	0.61	0.52	0.57	0.62	0.49	0.60	0.58	0.77	0.67
N-58	0.70	0.71	0.32	0.75	0.25	0.75	–	0.54	0.45	0.63	0.59	0.44	0.56	0.58	0.62	0.56
N-63	0.59	0.46	0.53	0.47	0.51	0.64	0.55	–	0.68	0.58	0.58	0.72	0.62	0.59	0.72	0.60
N-75	0.56	0.56	0.39	0.60	0.31	0.63	0.56	0.57	–	0.53	0.58	0.59	0.51	0.52	0.63	0.55
N-81	0.44	0.36	0.81	0.40	0.76	0.57	0.38	0.60	0.45	–	0.62	0.55	0.76	0.63	0.70	0.71
N-87	0.26	0.21	0.77	0.21	0.82	0.36	0.71	0.39	0.25	0.71	–	0.50	0.58	0.55	0.64	0.59
N-104	0.63	0.61	0.45	0.73	0.32	0.67	0.63	0.57	0.74	0.44	0.29	–	0.56	0.43	0.61	0.53
N-117	0.64	0.65	0.48	0.63	0.46	0.71	0.60	0.56	0.66	0.51	0.37	0.69	–	0.71	0.74	0.80
N-123	0.40	0.33	0.84	0.33	0.82	0.46	0.32	0.56	0.43	0.83	0.74	0.38	0.46	–	0.64	0.74
N-135	0.76	0.62	0.43	0.67	0.34	0.70	0.69	0.61	0.68	0.45	0.25	0.69	0.65	0.43	–	0.81
N-147	0.80	0.67	0.54	0.73	0.37	0.79	0.71	0.69	0.66	0.56	0.32	0.75	0.69	0.45	0.73	–

1.N-02
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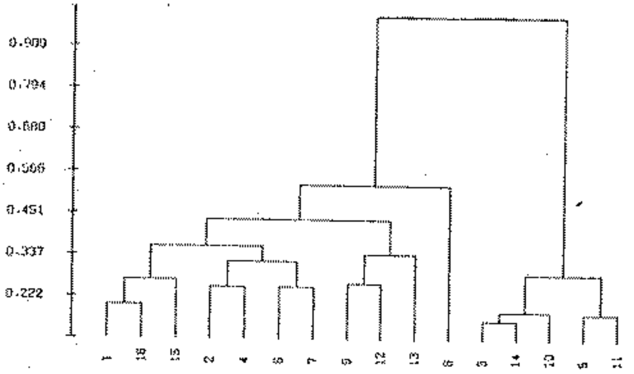
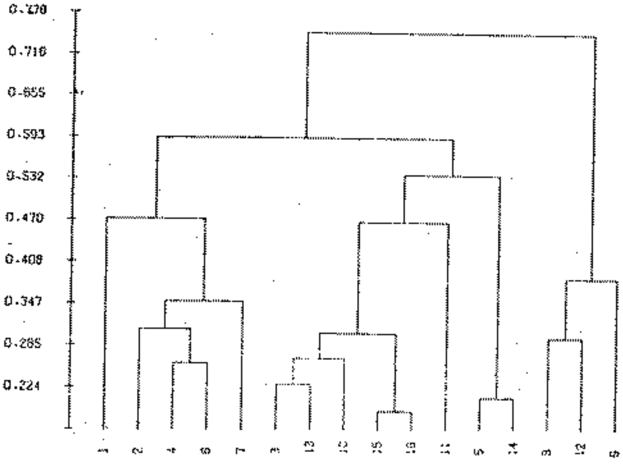
15.N-135
16.N-147



CLUSTER ANALYSIS DENDROGRAM FOR BRAY-CURTIS SIMILARITY INDEX



CLUSTER ANALYSIS DENDROGRAM FOR BRAY-CURTIS SIMILARITY INDEX

FIG. 8.—Matrix of similarity values for panels at week 24 (lower left) and week 30 (upper right). Corresponding cluster diagrams for week 24 (TOP) and week 30 (BOTTOM). Abscissa in diagrams shows each of 16 permanent panels; ordinate is a distance measure (1-similarity).

	N-02	N-08	N-24	N-33	N-43	N-50	N-58	N-63	N-75	N-81	N-87	N-104	N-117	N-123	N-135	N-147
N-02	-	0.56	0.64	0.68	0.64	0.46	0.58	0.54	0.31	0.50	0.59	0.47	0.63	0.38	0.65	0.66
N-08	0.41	-	0.53	0.63	0.67	0.50	0.70	0.52	0.35	0.45	0.50	0.47	0.46	0.31	0.57	0.64
N-24	0.35	0.66	-	0.45	0.54	0.46	0.36	0.40	0.42	0.36	0.58	0.41	0.59	0.44	0.79	0.65
N-33	0.63	0.29	0.15	-	0.69	0.62	0.77	0.59	0.32	0.65	0.68	0.65	0.60	0.29	0.49	0.72
N-43	0.31	0.52	0.61	0.24	-	0.60	0.63	0.68	0.52	0.60	0.62	0.60	0.59	0.37	0.60	0.68
N-50	0.34	0.75	0.70	0.28	0.52	-	0.57	0.47	0.40	0.47	0.61	0.51	0.51	0.33	0.54	0.64
N-58	0.63	0.51	0.51	0.64	0.40	0.52	-	0.58	0.28	0.61	0.57	0.57	0.49	0.22	0.43	0.60
N-63	0.72	0.38	0.32	0.81	0.38	0.41	0.70	-	0.60	0.57	0.58	0.64	0.52	0.32	0.47	0.57
N-75	0.27	0.24	0.25	0.77	0.27	0.38	0.56	0.80	-	0.40	0.47	0.44	0.43	0.59	0.48	0.42
N-81	0.66	0.45	0.41	0.63	0.37	0.48	0.66	0.72	0.72	-	0.59	0.69	0.59	0.32	0.39	0.54
N-87	0.42	0.63	0.72	0.34	0.58	0.79	0.59	0.48	0.44	0.58	-	0.68	0.70	0.43	0.57	0.74
N-104	0.58	0.19	0.13	0.85	0.14	0.71	0.54	0.74	0.74	0.61	0.30	-	0.56	0.30	0.40	0.64
N-117	0.71	0.40	0.46	0.62	0.50	0.49	0.73	0.74	0.67	0.75	0.59	0.52	-	0.43	0.59	0.67
N-123	0.46	0.54	0.57	0.32	0.74	0.59	0.49	0.48	0.38	0.50	0.68	0.26	0.56	-	0.47	0.43
N-135	0.38	0.70	0.68	0.34	0.65	0.73	0.52	0.46	0.37	0.46	0.66	0.23	0.61	0.70	-	0.68
N-147	0.84	0.48	0.33	0.59	0.35	0.41	0.68	0.66	0.58	0.60	0.48	0.52	0.68	0.48	0.50	-

1.N-02
2.N-08
3.N-24
4.N-33
5.N-43
6.N-50
7.N-58
8.N-63
9.N-75
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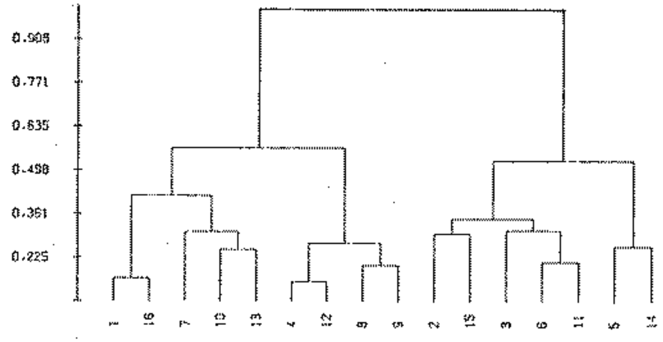
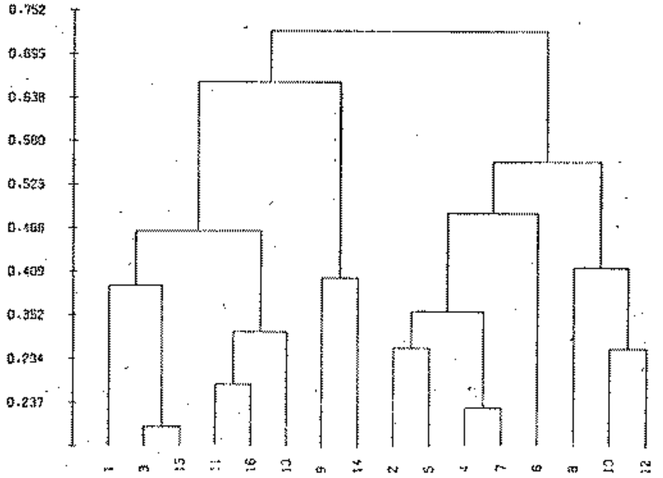


CLUSTER ANALYSIS DENDROGRAM FOR BRAY-CURTIS SIMILARITY INDEX



CLUSTER ANALYSIS DENDROGRAM FOR BRAY-CURTIS SIMILARITY INDEX

FIG. 9.—Matrix of similarity values for panels at week 39 (lower left) and week 48 (upper right). Corresponding cluster diagrams for week 39 (TOP) and week 48 (BOTTOM). Abscissa in diagrams shows each of 16 permanent panels; ordinate is a distance measure (1-similarity).

first year of colonization. Despite the fact that our experimental approach includes both destructive and non-destructive sampling techniques, with the possibility of incorporating further variability by combining their resultant data, we have found that different panels in a series tend to have fairly similar totals with respect to both of these parameters. In this particular locality, panels were initially similar with respect to major colonizing species. However, in other areas where settlement is more variable, subsequent panel development may be more variable as well.

At first glance, our results may seem to contrast those of SUTHERLAND (13) who found the fouling community extremely variable in North Carolina, as did BOYD (1) in California. Their results suggest that historical events on individual panels affect subsequent development, and if panels in a series vary, outcomes will differ. These findings raised doubts about much of the earlier fouling research which was based on sequential collection of panels considered to have similar developmental histories.

On the other hand, reports of minimal variability between replicate panels have also come to light. MOOK (7) found little variability among 5 panels observed for 1 month in Florida. OSMAN's (10) Massachusetts fouling study shows that variability within a series of panels is relatively low, as do some Hawaiian data (11).

In part, the discrepancies in conclusions by these workers seem to depend upon whether emphasis is given to individual species identities or to total species counts. If individual species presences are of paramount importance, variability appears higher than if species counts, obscuring particular identities, are investigated.

Our analyses of variability in Puget Sound for total species counts and total percent coverage of panels suggest that if these are the parameters of interest, a good estimate of the mean values can be obtained without extensive series of panels. The 95 % confidence limits around the mean are seldom decreased substantially beyond sample sizes greater than 10 at our Phinney Bay site. These values generally span 10 % on either side of the mean. If factors impose time constraints on the number of panels which can be observed, our analyses suggest that the benefit generally diminishes beyond sample sizes of greater than 10 at most time periods. However, we do not wish to imply that there is no benefit in taking greater numbers of samples when possible; increased sample size often results in additional information and a greater degree of certainty, and we therefore recommend it whenever feasible.

ACKNOWLEDGMENTS

We would like to acknowledge the generous help of C. D. LONG and R. A. CLONEY for their aid in identifying polychaetes and tunicates, respectively. Discussions with T. S. ENGLISH, E. GALLAGHER, P. A. JUMARS, T. W. SCHOENER and R. F. L. SELF were most helpful.

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MACROFOULING PROBLEMS ASSOCIATED WITH OCEAN THERMAL ENERGY CONVERSION (OTEC) UNITS

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JEFFERY MARCUS, Ph.D. *

USA

ABSTRACT

Macrofouling problems of the Ocean Thermal Energy Conversion (OTEC) machine have not been considered in detail elsewhere. Two categories of potential problems exist: problems of the functioning of the OTEC machine as affected by macroorganisms and effects of the machine on the environment. Herein we have chiefly considered the first category.

Experiments to test growth rates on each of the substances potentially to form major portions of the hull were carried out at depths equivalent to various hull design depths, from 0 to 60 ft in the Florida current off Miami, Florida. Materials were galvanized steel, raw steel, PVC, aluminum and concrete. These were suspended at 5 ft intervals and observed at three week intervals, some being brought in, others being measured and weighed only after 90 days. The organisms attached on a series of other artificial structures having the same basic construction materials in potential OTEC sites of the Gulf of Mexico and the south and southeast coast of Puerto Rico, as well as Hawaii, were examined. Lists of potential major fouling organisms were derived from this.

A scoping calculation to estimate the amount of maximum organismal growth on the hull which might affect density of the OTEC machine was made and it was found that over ten various hull designs, the maximum potential fouling growth would be 2.5 % of the weight of the OTEC machine, an amount which could be compensated by working ballast.

The OTEC machine may serve as a matrix for attached organisms in the sense of an artificial reef. Siting geographically and distance from shore in terms of recruitment of attached animals and feed habits of migratory animals should be considered carefully. Both structurally and functionally, this artificial reef could benefit local nearshore fisheries with appropriate technology. Detrimental effects of the OTEC machine on the artificial reef are not considered herein.

INTRODUCTION

The success of Ocean Thermal Energy Conversion may depend on the efficient control of fouling of microorganisms on heat exchangers, where even a thin biofouling film could severely affect heat transfer (CORPE, 1978; BRYERS *et al.*, 1979; DE PALMA *et al.*, 1979; SASSCER *et al.*, 1979). Macrofouling of hull, intake, outflow and other structures could also create severe problems for the operation of OTEC, *e.g.*, blockage of warm and cold water intake and outflow systems and/or causing a change in buoyancy which might threaten stability.

Work on the effects of macrofouling has been scant. A notable exception is the work of DE PALMA (1978), who predicted the type of attached species, distribution with depth, and rate of colonization which may occur on a generalized OTEC structure. His information is based on extensive investigation of fouling communities at nearshore and offshore sites worldwide, and specifically in the Straits of

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Florida and Bahamas (De Palma, 1968). He used test panels of wood-asbestos for collecting samples.

Since the work of De Palma (1968, 1972, 1978), considerable progress has been achieved on the structural design, components, and deployment of OTEC. Materials to be used for OTEC (List 1), dimensions of various OTEC designs (Table 1), and some location sites are now delineated. Mini-OTEC (a test plant) began functioning offshore from Keahole Point, Hawaii, in August, 1979. OTEC-1, a larger-scale model, is scheduled to begin operation on April 1, 1980, and is located west of the island of Hawaii (Svensen, 1979). A research platform (Landing Craft Utility) is also constructed to test biofouling and corrosion at Punta Tuna, Puerto Rico, a proposed OTEC site (Sasscer *et al.*, 1979). These test facilities and advancements in OTEC design provide an excellent foundation for more detailed analyses of macrofouling on OTEC plants.

Accordingly, the objectives of this study are:

LIST 1

PROPOSED OTEC CONSTRUCTION MATERIALS WHICH MAY BE COLONIZED BY FOULING ORGANISMS

Component	*Material*
Hull of plant	Concrete Steel
Heat exchangers	Stainless steel Aluminum Titanium
Cold water pipe (CWP)	Polyethylene Fiberglass Fiber-reinforced rubber

TABLE 1

SHAPE, DIMENSION, DEPTH AND POWER OUTPUT OF OTEC HULL DESIGNS (SUPPLIED BY R. W. HAZELWOOD AT GLOBAL MARINE DEVELOPMENT, NEWPORT BEACH, CALIFORNIA)

OTEC design	*Shape & material*	*Lower output (in MWe)*	*Surface area (in m²)*	*Depth (in m)*
OTEC-1	Tanker - steel	1	4,110	7.3
Applied Physics Lab	Rectangular barge - steel	40	6,235	16.8
Applied Physics Lab	Rectangular barge - concrete	40	8,143	18.3
Applied Physics Lab	Rectangular barge - concrete	10-20	10,275	19.8
Spar Configuration	Cylindrical	10	13,900	45.7
Spar Configuration	Cylindrical	40	15,700	50.3

1) to identify the potential biotic community which may develop on an offshore OTEC plant; 2) to determine the rate of colonization of the attached macroorganisms; and 3) to consider how the attached community may affect the operation and efficiency of the plant. Test panels are being examined, along with existing structures at OTEC test sites, *e.g.*, mini-OTEC in Hawaii and the Landing Craft Utility in Puerto Rico. Data from previous fouling studies are used in scoping calculations to determine if the weight of attached organisms would severely affect the buoyancy of the plant.

METHODS AND RESULTS

A. Caribbean Attached Organisms

Test panels of materials likely (as of fall, 1979) to be used in external OTEC construction (hull and pipe) were placed in the Gulf Stream south of Key Biscayne, Florida, at Fowey Light at depths ranging from the surface to 18 m below the surface. Each panel (15 × 30 cm) of galvanized steel, raw steel, PVC, aluminum, and concrete was weighed and placed in seawater for 48 hr (to age) prior to being positioned at the test site. The panels were placed on two vertical lines (A and B) of polypropilene rope (7/8 inch diameter) moored to a reef and held vertical with surface buoys. Five panels of each material were placed on line A and were exposed for a period of thirty days while an identical set was positioned on line B at the same depths for ninety days. Attached organisms on line A will be identified, counted, measured and weighed. The panels were then to be cleaned and returned to line A for further monthly tests. Longer-term colonization is measured by the panels on line B, collected and treated in the same manner. Panels of the same dimensions and material were also situated in two nearshore sites in Biscayne Bay, Florida, at a depth of approximately 3 m so that a comparison with offshore results might be obtained. The test panels were positioned in November, 1979.

B. Pacific Attached Organisms

Panels of PVC were placed at approximately 9 m depth at the Mini-OTEC site in Hawaii for approximately 18 months. Mr. Hank White, Operations Manager of the Natural Energy Lab. of Hawaii, kindly sent us one of these panels for analysis. The attached community was identified by Julio García-Gómez, of the University of Miami, and is described in List 2. We also have some information on the

LIST 2

ORGANISMS FOUND ON PIPE SENT BY NATURAL ENERGY LAB OF HAWAII

Algae: Rhytophyta
Spyridia sp.
Polysiphonia sp.
Jania sp.
Mesophyllum sp.

Protozoa: Sarcodina: Foraminifera - several species.
Porifera: Unidentified calcareous sponge
Coelenterata: Scleractinia: Orbicellidae - *Cyphastrea ocellina*
Nemertinea: Unidentified species
Nematoda: Unidentified species
Annelida: Polychaeta - several species
Mollusca: Gastropoda: *Littorina* sp.
Bivalvia: *Pinctada* sp.
Arthropoda: Crustacea
  Ostracoda: Several species
  Isopoda: Aselloidea: One species
  Amphipoda: Gammaridea: Several species
  Caprellidea: One species
Bryozoa: Ectoprocta - *Schizoporella* sp.
Echinodermata: Ophioroides: One species
Echinoidea: One species

marine life found on the surface littoral, sublittoral and parguera in Puerto Rico given us by Mr. VANCE VICENTE, of the University of Puerto Rico (List 3); however, we will have no data on colonization of test panels or of the Landing Craft Utility at the Punta Tuna site until early 1980, when the Landing Craft Utility is in operation.

LIST 3

NOTES OF CONVERSATION WITH VANCE VICENTE, MAY 29, 1979

Punta Tuna:
- Shallow
- Surface littoral rocky communities
  - Wave action on:
    - *Laurencia papillosa*
    - Barnacles
    - Mussels
    - No sponges
    - *Sargassum*
    - Ulva - if nutrient-rich
    - Amphipods and algae
    - Intertidal snails
    - Fishes
    - *Echinometra* - urchin (found on cement structure)
- Sublittoral: *Laurencia*
  - Sponges: encrusting
    - *Microceona*
    - *Chondrilla*
  - Corals: fast growing
    - *Diploria*
    - *Favia*
    - *Siderasteria*
    - *Porites*
    - *Millepora*
  - *Cladophora*
  - *Enteromorpha intestinales*
  - Red and brown *Sargassum*
  - *Turbinaria turbinata*
- Parguera: Blue-green algae
  - Green algae
  - Barnacles, especially thermal
  - Oysters
  - Corals: *Favia fragum*
    - *Porites porites*
    - *Aeropora* sp.
  - Sponges - on high nutrient water
  - Algae

DISCUSSION

One of the main concerns of macrofouling is that the virtual weight of fouling organisms could affect the buoyancy and stability of the OTEC plant. Scoping calculations were done in an attempt to predict the severity of such a problem. The calculations were based on previous rates of fouling obtained in other studies (WOODS HOLE, 1952; DE PALMA, 1978) and applied to the various OTEC designs (Table 1). Table 2 gives the weight displacement in LT for each OTEC design and the weight of biofouling organisms which could accumulate after ten or eleven months. The percentage of barnacle fouling to total weight displacement of the OTEC designs ranged from 0.37 % (Applied Physics Lab.) to 1.68 % (Spar configuration). The percentage of mixed fouling to total weight displacement was in the same range, *i.e.*, 0.61 % (Applied Physics Lab.) to 2.51 % (Spar). These calculations show that the percentage weight of fouling organisms compared with the weight of the OTEC structure is not greater than 2.5 % for any OTEC design, though as much as 628 LT can accumulate in an eleven-month period.

DE PALMA (1978) predicted that after twelve years, the upper 18 m of the OTEC hull would be 100 % covered with hard-shelled species (*e.g.*, barnacles, molluscs, corals) and that at 30 m and 90 m, the hull would be covered with 50 % and 5 % hard-shelled organisms respectively. DE PALMA (1978) calculated that a substrate completely covered by hard-shelled organisms will increase in weight by approximately 17 kg m^{-2}. DE PALMA's predictions and weight calculations were used to calculate the expected mass of fouling organisms and their percentage weight to the entire hull of the different OTEC designs.

TABLE 2

POTENTIAL BIOFOULING OF EACH OTEC DESIGN. SCOPING CALCULATIONS

OTEC design	*Weight displacement ** *(in LT)*	*Barnacle fouling *** *(10 mo. exposure period)* *(in LT)*	*% of barnacle fouling to total weight displacement*	*Mixed fouling **** *(11 mo. exposure period)* *(in LT)*	*% of mixed fouling total weight displacement*
OTEC-1	16,300	101	0.62	164	1.01
Applied Physics Lab (10-20 MWe)	67,901	251	0.37	411	0.61
Spar Configuration (10 MWe).	20,360	341	1.68	511	2.51
Spar Configuration (40 MWe).	54,300	384	0.71	628	1.16

* Provided by VSE Corporation, Alexandria, Virginia.

** Based on *Balanus tintinnabulum* on navigation buoys in Florida. Colonization rate 5 lb/sq ft in 10 months (WOODS HOLE, 1952).

*** Based on records for Elbe lightships. Colonization rate 40 kg m^{-2} in 11 months (WOODS HOLE, 1952).

The results show that the biomass of fouling organisms and their percentage weight on the hull after a twelve-year period would be: 85.5 LT (0.19 %) for a 10-20 MWe Applied Physics Lab.; 86.9 LT (0.43 %) for a 10 MWe Spar configuration; 98.0 LT (0.18 %) for a 40 MWe Spar; and 34.2 LT (0.21 %) for a 1 MWe OTEC-1. These figures based on twelve years of fouling are in the same range as the calculations based on the fouling rates after ten or eleven months obtained in the study at WOODS HOLE (1952) and delineated in Table 2.

DE PALMA (1978) states that once a surface is totally covered, there is a minimal increase of added weight per surface area with time. This may explain why the fouling rates are similar even though some are based on ten to eleven month observations and others on a twelve-year prediction. The scoping calculations based on both studies indicate that buoyancy and stability of the OTEC plant will not be severely affected by fouling organisms, *i.e.*, the working ballast could offset the weight increase.

A second important macrofouling problem is potential clogging of the intake system, which would interfere with the efficient operation of the heat exchangers. OTEC-1 will have removable trash screens on the intakes; chlorination will abso be used with a continuous 0.05 ppm concentration and three fifteen-minute shock doses (each 1 ppm) daily. The chlorination will be injected into the system at the pump suction (R. W. HAZELWOOD, personal communication). These precautions may inhibit macrofouling at the intake junctures; however, the effectiveness of such precautions will remain unclear until OTEC-1 is in operation. Other remaining effects of macroorganisms on OTEC plant operation are macroalgal buoyancy changes and outflow clogging.

A second whole set of considerations is the effect of OTEC on the environment. If the efficiency of the OTEC plant is not impaired by attached organisms, OTEC may actually serve as a beneficial substrate in the formation of an artificial reef community. Such a reef would provide food (attached algae) and shelter (between algae and in and around attached animals). It could become a potential breeding ground for a wide range of fish. Workers at the University of South Alabama have reported that in the Gulf of Mexico, Liberty ships sunk at 15 to 30 m depth have a colonization of barnacles after the first week, followed by polychaetes, bryozoans, algae and hydroids within a year. Primary producers and consumers are soon followed by commercial fish such as grouper, red snapper and amberjack. The biota of the artificial reef community will depend on distance from shore for recruitment of larvae and juveniles, geographic location, and depth of hull. However, it is clear from other structures in subtropical and tropical waters serving as artificial reefs that colonization of an OTEC plant could be of great interest to the fishing industry. There might be small appropriate technological industries for nearshore islands with local fisheries, or larger-scale fisheries.

If attached organisms are creating a hindrance for OTEC, they are considered fouling organisms; if not, they may be considered colonizers of an artificial reef and initiators of an important food web. Once a community does develop, it may be looked upon as part of the environment and consequently protected by U.S. government policy (NEPA, 1969) if falling within the U.S. territorial limits.

In summary, it appears unlikely that buoyancy will be severely stressed in OTEC plants; however, continued monitoring of OTEC test structures and panels is necessary to determine the effects of fouling on OTEC operation, and concurrently the effects of OTEC on the environment.

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STONE BORING MARINE BIVALVES AS RELATED TO THE GEOLOGY OF MONTEREY BAY, CALIFORNIA

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USA

INTRODUCTION

A beachcomber walking the sandy beaches of the southern part of Monterey Bay can observe, during most seasons of the year, quantities of gray shale fragments that have been cast up by the waves from shallow subtidal waters. Many of these fragments show extensive cylindrical or pear-shaped excavations the size of one's thumb or larger. Usually the excavations are empty and give no evidence of what formed them, but often complete or incomplete shells of bivalves can be found fitting snugly in the burrow, and occasionally, after storms, shale fragments cast ashore contain living bivalve borers. In the northern part of Monterey Bay, along the shore at Santa Cruz, large boulders in the surf zone are pock marked with the holes made by boring bivalves at a time when the boulders were in shallow subtidal water. Also at Santa Cruz living bivalves bore into mudstone and shale in the reefs and cliffs of the intertidal zone. When one examines by diving on, or dredging, the rocky outcrops in shallow water, such as those under the kelp beds off Del Monte Beach in Monterey or off Capitola or Santa Cruz, one finds much of the exposed rock riddled by the excavations of numerous boring animals. The animals, the largest and most abundant being boring bivalves, are obviously an important part of the endolithic community and play a significant role in coastal erosion.

Historically, Monterey Bay has been a center for shell collecting by conchologists for more than a hundred years. Included in many of the early collections were representative bivalve borers of the families Mytilidae and Pholadidae, and Monterey Bay is the type locality for several species. SMITH and GORDON (1948) summarized these early studies and presented a list of all boring and nestling bivalves reported from Monterey Bay up to World War II. For many years after the SMITH and GORDON paper appeared, little work was published on stone boring animals in Monterey Bay. In recent years, however, there has been renewed interest in this important group of animals and several theses and published papers have been partially or totally devoted to them (BOOTH, 1972; BURNETT, 1972; CLARK, 1978; DONAT, 1975; HADERLIE, 1976, 1977, 1979; HADERLIE and DONAT, 1978; HADERLIE *et al.*, 1974; MINTER, 1971).

Since 1970, a continuous long term study on marine bivalve stone borers by students and staff of the Naval Postgraduate School in Monterey has been underway. This study has consisted of two parts. First, the horizontal and bathymetric distribution and substrate preference of living borers within Monterey Bay have been investigated. This has involved extensive shore collecting, shallow water diving, and shipboard dredging operations. Second, experimental studies aimed at determining reproductive seasons, settling times, growth rates, and longevity of individual borers have been carried out. These studies have made use of experimental stone panels placed in the sea at various times and depths and for varying periods and then recovered and examined for evidence of bivalve borer settlement and growth. As part of these experimental studies living pholads and boring mytilids have been placed in artificial burrows in stone, returned

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to racks on the sea bottom, then recovered periodically for radiographic analysis of growth.

This paper presents the results to date of the first part of this study, namely the identity, distribution abundance, and substrate preference of stone boring bivalves of the families Mytilidae and Pholadidae and associated nestlers in Monterey Bay. The results of the experimental part of the study will be published later.

I want to acknowledge the help of many people, but especially Captain REYNOLDS and the crew of R/V ACANIA for their unfailing cooperation and help during many arduous hours of dredging operations over many years in all weather conditions in Monterey Bay. Also, I want to thank my colleagues and students who assisted in the hundreds of shallow water Scuba dives for making observations and collections, photography, or recovery of lost gear such as dredges. These include G. C. BOOTH, G. W. CLARK, W. DONAT, J. C. MELLOR, C. S. MINTER, and J. NORTON. In the early part of the study Dr. Ruth TURNER of Harvard assisted in the identification of borers and has given advice on many phases of the work. Drs. R. S. ANDREWS and W. C. THOMPSON of the Naval Postgraduate School and Dr. H. G. GREENE of the U.S. Geological Survey helped in sorting out the complex geology of Monterey Bay, and Florence LEE-WONG of the U.S. Geological Survey made the petrographic analyses of thin sections of various rock samples. The Office of Naval Research, Oceanic Biology Program, has provided long term financial support for this project, and the Naval Postgraduate School Research Foundation Program has assisted in the intertidal part of the project.

GEOLOGY OF MONTEREY BAY

As this study involved the distribution of bivalves boring into the sedimentary rocks of Monterey Bay it was essential to determine the specific nature of the rocks themselves and the general geology of the area. Fortunately, a thorough marine geological investigation of Monterey Bay has been underway for many years using modern geophysical tools and techniques, and the results of this investigation was published recently (GREENE, 1977). Doctor GREENE has examined many of our dredged samples and has also walked the shore with us and helped us understand the complex geological features of the Santa Cruz shoreline.

Monterey Bay is a large open embayment along the central California coast some 115 km south of San Francisco (see Fig. 1). The mouth of the Bay is about 37 km in width when measured from Point Santa Cruz in the north to Point Pinos in the south. The shoreline at the southernmost part of the Bay, on the Monterey Peninsula, is a rocky headland composed of Santa Lucia granodiorite of Cretaceous age. From Monterey eastward and north to Soquel Point there are broad sandy beaches backed by dune fields in the south and cliffs in the north. The shoreline in the vicinity of Santa Cruz is composed of steep bluffs with flat-topped terraces. These sea cliffs are Quaternary marine terrace deposits which overlie Pliocene Purisima Formation at Point Santa Cruz. This latter formation is exposed as yellow sandstone and siltstone in the intertidal zone. To the west of Point Santa Cruz the sea cliffs are composed of Pliocene Santa Cruz mudstone overlying layers of chert of Miocene Monterey Formation. This latter formation extends as broad terraces or finger reefs interspersed with sandy pockets into the intertidal and subtidal zones.

The subtidal topography of Monterey Bay is diverse and complex. The sea bottom relief is dominated by the Monterey Submarine Canyon which originates less than 2 km west of Elkhorn Slough and extends westward for over 90 km as a deep, V-shaped cut in the continental shelf. This canyon exhibits greater relief features than any on the nearby shore and essentially bisects Monterey Bay. Within the Bay the main canyon meanders and is joined by a major tributary, Soquel Canyon, coming from the north. The remainder of the Bay bottom is a relatively flat, gently sloping continental shelf, covered with unconsolidated sediments and interrupted by a few rocky reef outcrops. GALLIHER (1932) was the first to publish information on the location and lithologies of these rocky outcrops. SHEPARD and EMERY (1941), MARTIN (1964), and

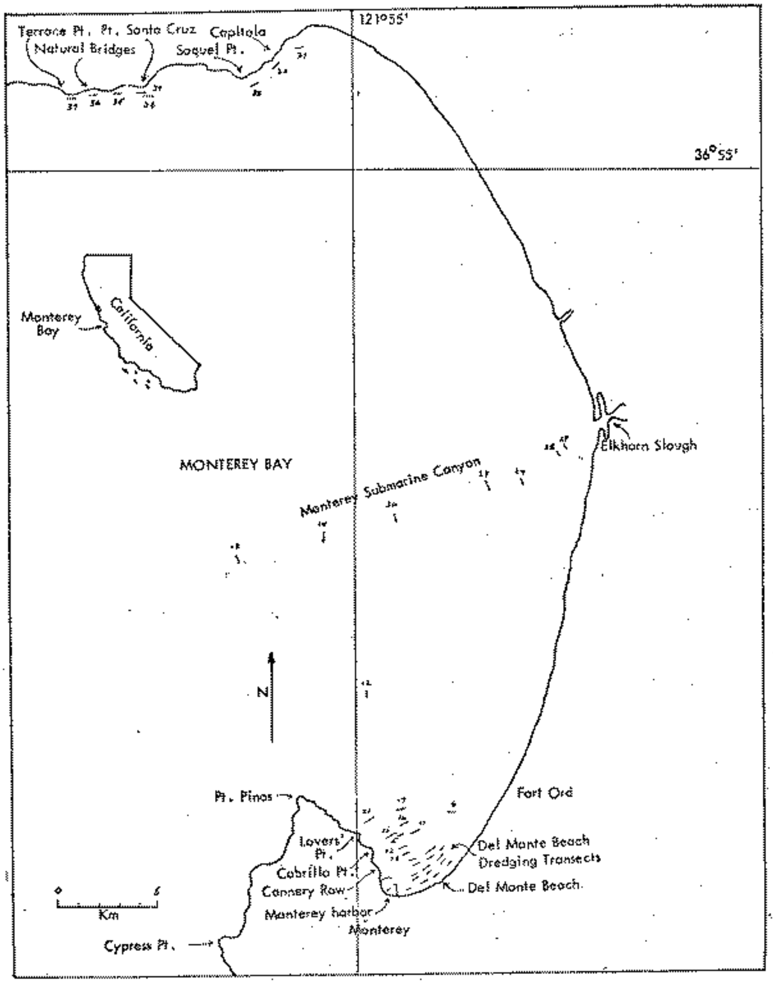

FIG. 1.—Map of Monterey Bay Showing General Location of Dredging Transects, Dredge Haul Numbers Shown on Some Transects (see Table 1).

GREENE (1977) have extended these observations in many details and have also reviewed the extensive literature on the geology of Monterey Bay. During these previous studies, and from dredge hauls made during the present investigation, rock samples from many of these outcrops and from the walls of the Monterey Submarine Canyon have been obtained. Samples of porphyritic biotite granodiorite have been dredged from off Point Pinos and from the south wall of the Monterey Canyon. This granitic rock that forms the basis of the Monterey Peninsula is apparently also the dominant basement rock under Monterey Bay. The sedimentary rocks dredged from the bottom of the Bay are mudstones, siltstones, sandstones, and conglomerates derived from the Monterey Formation of middle Miocene age and from Pliocene Purisima Formation.

The Monterey Formation has been investigated intensively (BRAMLETTE, 1946). It occurs in California from just north of San Francisco to south of Los Angeles and under the coastal range may be 1000 m or more in thickness. In most areas the upper part of this formation is composed of diatomite and less pure diatomaceous rocks. Deeper layers consist of hard siliceous rock called porcelanite or chert. This hard material shows few remains of the original diatom shells. A characteristic feature of the chert layers is the presence of large boulder-like concretions that are carbonate cemented nodular masses of the sedimentary material forming the surrounding chert beds. The concretions can be observed in place in the flat reefs in the intertidal zone to the west of Point Santa Cruz, and as free boulders in the surf zone. On the Monterey Peninsula the Monterey Formation unconformably overlies the granitic basement rocks. Along the shore at Del Monte Beach in Monterey, the Monterey Formation is covered with sand dunes and a sandy beach, but is exposed subtidally in shallow water in the areas of the kelp beds. In this area of shallow water, and further offshore, the concretions so characteristic of this formation either lie partially embedded in the cherty matrix or lie free on the bottom as small to large rounded boulders. Further offshore samples of chert from the Monterey Formation have been dredged from the south wall of the Monterey Canyon 10 km north of Point Pinos, and from the west wall of Soquel Canyon. As mentioned above, the Monterey Formation occurs in the shallow subtidal zone and intertidally as part of the reefs, terraces, and sea cliffs west of Point Santa Cruz at the north end of the Bay.

The second major type of sedimentary rock found in the Monterey Bay area is the Purisima Formation that is mainly of Pliocene age but may include some strata of Pleistocene age. This formation is widely distributed, and in the Santa Cruz mountains may reach of thickness of over 1700 m. At the north end of Monterey Bay it is found as the lower part of the sea cliffs at Point Santa Cruz. Offshore rocks of the Purisima Formation have been dredged from many localities. Specific locations include the seaward end of Soquel Canyon, at isolated localities along both north and south walls of the Monterey Canyon from the edge of the continental shelf to near the head of the canyon, and in shallow subtidal water off Capitola and Santa Cruz. The rock was either greenish-gray in color and composed of medium to fine-grained sandstone and siltstone, or was a dark gray silty mudstone. These rocks were often fossiliferous with many well-preserved megafossils of molluscs, echinoderms, and barnacles. The dredged samples of Purisima rock often consisted of irregular boulders or pebbles.

AREA OF STUDY AND DREDGING TRANSECTS

This study has been limited to Monterey Bay, which is here defined as the area to the east of a line running from Point Pinos on the Monterey Peninsula to Terrace Point west of Santa Cruz in the north. Only one dredge haul was made outside of this area, and that was on the south wall of the Monterey Canyon 2 km northwest of Point Pinos where only granite rock was recovered.

The area of most intense study, and that from which we have the most complete data, is the shallow subtidal zone off Del Monte Beach to the east of Monterey harbor at the most southerly end of Monterey Bay (Fig. 1). This area is roughly defined by the extensive kelp bed made up primarily of *Macrocystis pyrifera* (Linnaeus, 1771) whose holdfasts are attached to the discontinuous outcrops of shale of the Monterey Formation. The water depth in the area of shale outcrops is from 10 to 20 m. The structural geology of this area is very complex, for it lies within the Monterey Bay Fault Zone (GREENE, 1977). The contact between the siliceous shale of the Monterey Formation on the east and the Santa Lucia granodiorite to the west lies near Monterey Municipal Wharf No. 2 at the western edge of the Del Monte Beach study site. This contact is covered with sand. Seismic reflection profiling has shown that the Monterey Formation off Del Monte Beach is heavily faulted with synclines and anticlines generally sloping northwest (GREENE, 1977). In most of the area the bottom consists of relatively flat smooth shale, sometimes covered with sand to varying thickness, at other times completely exposed except for low lying sand pockets. In roughly the middle of the study site off Del Monte Beach, the topography is much more rugged with hummocks and ledges distributed parallel to the trend of the Tularcitos Fracture Zone which enters the Bay from the southeast. Some of these ledges are continuous ridges rising 2 m or more above the adjacent bottom and running several hundred meters seaward. The shale in this area has been examined and sampled repeatedly over the past 10 years by Scuba diving, and the benthic fauna and flora, including the distribution of several species of boring bivalves, have been investigated (BOOTH, 1972; BURNETT, 1972; HADERLIE, 1976; HADERLIE *et al.*, 1974; MINTER, 1971).

The present investigation has continued these studies and extended them seaward by using shipboard dredging techniques to sample the exposed shale in deeper water of Del Monte Beach and throughout Monterey Bay. Some dredge hauls were made in areas previously studied by shallow water diving in order to recover larger samples of rock substrate than can be collected conveniently by divers.

In this study, the plan was to sample as many of the sedimentary rock outcrops within Monterey Bay as possible. Areas of known exposed granite rock, such as in the shallow water around Point Pinos, were avoided, for the granodiorite is too hard and chemically resistant to be bored by marine animals. Our dredging operations concentrated, therefore, on areas where either the Miocene Monterey Formation or the Pliocene Purisima Formation was known or suspected to be exposed above the soft unconsolidated bottom sediments. In shallow water from 10 to 20 m deep around the periphery of Monterey Bay such areas of exposed sedimentary rock can often be located by the kelp beds that occur only where holdfasts can attach to solid substrate. The beds of *Macrocystis pyrifera* growing in the water off Del Monte Beach in general define the areas of exposed Monterey shale, and those off Capitola, Soquel Point, and off Santa Cruz at the northern end of the Bay are indicative of outcrops of Purisima Formation. In Monterey Bay, *Macrocystis* does not occur generally in water deeper than 20 m, so the location of exposed reefs in deeper water is more difficult and in the past has depended on systematically sampling the bottom with grabs or dredges. The first comprehensive dredging operations in Monterey Bay were carried out by the steamer *Albatross* in 1904 and many of the sedimentary reefs in deeper water were charted at that time (Bureau of Fisheries, 1906). In more recent years other areas of exposed rock on the bottom of the Bay have been located by dredging and by seismic relection profile techniques (GREENE, 1977).

During this investigation, we have successfully collected bottom samples on 40 dredge hauls in Monterey Bay (Fig. 1). As will be described below, each operation consisted of towing the dredge for a distance of from 100 to 500 m along the bottom, thus we have sampled along a series of short transects. Some of these transects are rather close together, particularly those off Del Monte Beach in the southern part of the Bay.

In addition to the subtidal areas of Monterey Bay described above, we have surveyed the intertidal zones for sedimentary rocks which might harbor bivalve borers. At the southern end of Monterey Bay along the shore of the Monterey Peninsula only granitic rock is exposed in the intertidal zone and no bivalve borers can penetrate this hard basement material. From Monterey Harbor around the Bay to Soquel Point in the north, the shore consists of sandy beaches. But from Soquel Point westward to Terrace Point, sedimentary rocks of both the Purisima Formation and the Monterey Formation are exposed in the intertidal zone as reefs or sea cliffs. We selected one of these reefs just to the west of Point Santa Cruz for intensive study of bivalve borers. The results of this latter study has appeared as a student thesis (CLARK, 1978) and will be reviewed later in this paper.

METHODS AND EQUIPMENT

Our objectives in this study were to determine the identity, density of numbers of individuals, distribution horizontally and with depth, and substrate preference of mytilid and pholad borers in sedimentary rocks in and around Monterey Bay. As these borers are hidden, sometimes deeply, in the substrate, with only the distal ends of the siphons projecting out of the burrow, in order to find, identify, and count the borers it is usually necessary to mechanically break the rock apart and remove the animals one at a time from their burrows. The shale was broken apart while diving by using hammer and chisel or by the use of an underwater jackhammer operated by pneumatic pressure from a Scuba tank. By removing and keeping representative living mytilid and pholad borers in sea water aquaria we were able to study the size, morphology, and color of the extended siphons after the animals had been positively identified using shell characteristics. With this information we were able, while diving in shallow water, to identify and quantify many of the bivalve borers found in the Monterey shale off Del Monte Beach. A photographic catalogue of typical siphons with the animals *in situ* in subtidal rock has been prepared (see BOOTH, 1972; HADERLIE *et al.*, 1974; and MINTER, 1971, for details of techniques and representative photographs).

In the intertidal shale from near Point Santa Cruz, it was impossible to find or identify bivalve borers by examining the substrate, for the area was investigated during periods of low tide and all siphons were withdrawn into the burrows. Here it was necessary to excavate representative samples or rocky substrate by breaking apart the rock with hammer and chisel in order to expose and remove the borers. In hard chert this was a laborious process; and it was difficult to recover uninjured animals. Details on techniques and equipment used in the Santa Cruz intertidal study can be found in the thesis by CLARK (1978).

One major aim of this investigation was to sample sedimentary rock for borers in water below diving depths in Monterey Bay and to collect large rock samples from shallow water that were impossible to recover by diving. To accomplish this aim, various dredging techniques and kinds of equipment were employed. The Naval Postgraduate School's R/V ACANIA was used for most dredging operations. The dredging winch on ACANIA is a Sea-Mac Model 2500 (manufactured by Harvey Lynch in Houston, Texas), and it carries a spool of 1700 m of 1.3 cm wire which is led over the stern through a block on an A-frame. On some of the deeper stations over the Monterey Submarine Canyon, the AGOR USNS DE STEIGUER was employed, utilizing the deep sea dredging winch and cable.

In the early part of this study, the dredges used, particularly in the shallow water off Del Monte Beach, were various small and fairly light biological dredges available commercially. These proved unsatisfactory, for they could not break off sizable pieces of hard substrate without breaking the weak link or bridle on the dredge. We therefore fabricated two types of heavy duty dredges that have performed relatively well most of the time. The first of these was a pipe dredge made of a stainless steel cylinder 45 cm in diameter and 1 m long. The walls of the cylinder were 0.7 cm thick. A three-parted bridle of 1.4 cm chain was attached to the leading edge and the trailing end of the cylindrical pipe was closed off with a grid of 2 cm diameter rods spaced 5 cm apart. This type of pipe dredge is very rugged and has been used successfully to break off pieces of hard chert and even granite from the walls of the Monterey Canyon. For our purposes, however, this dredge was somewhat unsatisfactory, for it was able to recover only relatively small pieces of substrate due to the limiting diameter of the dredge opening. It also covered a very limited swath along the towed transect. Furthermore, in sampling on the walls of the Monterey Canyon, the pipe dredge often filled up with dense, stickly clay soon after it touched bottom and subsequently on the tow, even if the dredge encountered solid substrate, it did not collect any rock because the pipe was already full of clay.

The second type of device fabricated was a heavy duty chain bag dredge, and this has operated well in most localities. The dredge consisted of a heavy steel frame made of stock 1.5 cm thick and 15.5 wide. The four pieces of the frame were welded together forming a rectangle 45 cm by 85 cm. At the forward edge of the frame a four-parted bridle consisting of 1.0 cm chain was secured by shackles through holes in the frame. The trailing edge of the frame had attached to it a chain bag extending back 1 m. The bag was made of 0.7 cm chain with mesh openings of 12 cm with welded links securing each point where one strand of chain crossed another. This chain bag dredge has successfully broken off and collected large pieces of chert and mudstone and has scooped up free concretion boulders from the bottom of Monterey Bay. It, too, often became clogged with heavy clay, but not to the extent of the pipe dredge. In shallow water in the kelp beds, large holdfasts broken off occasionally blocked the mouth opening of the dredge and prevented successful recovery of rock samples.

Dredging is a very haphazardous operation and attempts to break off and recover sizable pieces of heavy solid substrate is a difficult operation and puts a severe strain on all equipment. On many occasions, particularly when dredging for the hard, dense Purisima Formation off Santa Cruz, a transect often had to be covered many times before a sample was successfully recovered. Several chain bag dredges were lost due to parting of the heavy towing cable or chain bridle after the dredge had struck a non-yielding ledge. The gearing mechanism on the winch was also damaged on several occasions. An improved hydraulic automatic release mechanism installed on the dredging winch on ACANIA during the later part of this study resulted in fewer hang-ups and no lost or damaged equipment.

Attempts were made to locate and sample most of the sedimentary rock outcrops in Monterey Bay. In some cases specific areas were re-visited where earlier workers had recovered rock while dredging. This was particularly true of the dredging stations on the south wall of the Monterey Canyon. In other areas, such as in the shallow water off Del Monte Beach and off Santa Cruz, parallel tows were made through the kelp beds at progressively deeper locations. Beyond the kelp beds, where we had no idea if any solid substrate was exposed, random tows were made somewhat parallel to one another and running generally from southwest to northeast. In this way, a substantial part of the bottom was sampled in the southern bight of the Bay south of 36° 38' 30" N (a line running east from Point Pinos to Fort Ord). The only area sampled in the middle part of southern Monterey Bay was at Dredging Transect No. 12, for this locality showed up on the ship's precision depth recorder as a well-defined exposed reef in water 90 m deep. Unfortunately, the dredge was snagged and only a small sample of chert was recovered. During the present survey no sampling was done on the north wall of the Monterey Submarine Canyon nor in deep water on the shelf in the northern part of the Bay. Earlier studies on the self area north of the Monterey Canyon have shown that it is covered with unconsolidated sediment.

After deciding on the specific locality to be sampled, the dredge was lowered to the bottom, sufficient cable was run out so that the dredge would not lift off the bottom, then it was towed slowly over the substrate. The distance towed varied from place to place. If the behavior of the towing cable indicated that the dredge had been hitting solid substrate and breaking off pieces of rock so that the chain bag was full or nearly so, the dredge was recovered after having passed over 100 m or less of bottom. In other cases the dredge was towed for up to 500 m, sometimes picking up rock of the very end of the tow, sometimes coming up empty. If the dredge collected a sample early in the tow, it was recovered and then lowered again and the tow continued along the same transect. Thus, the samples of rock recovered came from various places along the transect, but we were never sure where the dredge actually collected the sample.

On the south wall of the Monterey Canyon the usual dredging technique was to position the ship over the deep part of the Canyon, lower the dredge to the bottom, then allow the ship to drift slowly south or east so that the dredge would be dragged upward over the wall to the edge of the shelf.

The location of various dredging transects is shown in Fig. 1, and Table I lists the various dredging operations and the recovered samples. The position of the ship at the beginning and end of each transect was determined by visual bearings when close along shore or by Loran C when offshore. The depth of water and amount of dredging cable out was then used to estimate the path of the dredge along the bottom. This was then plotted on a Standard No. 18685 (formerly C and GS No. 5403) chart of Monterey Bay. This chart with the plotted transects is on file in the Department of Oceanography, Naval Postgraduate School. In Fig. 1, and in the location column of Table I, only the general locality and water depth of the transects are given.

When a sample of recovered rock was brought to the deck of the ship it was immediately examined to determine the type of rock and if there was evidence that the sample had been broken off or merely picked up as it lay free on the bottom. If the sample was small it was measured then broken up im-

TABLE I

DREDGING HAULS, SAMPLES RECOVERED, AND BORERS AND NESTLERS COLLECTED

Dredge haul No.	*Date*	*Depth & location*	*Substrate sample*	*Sample volume (cm³)*	*Relative abundance, vacant bare holes*
1	21 Mar 1974	22 m, off Del Monte Beach	Chert block	125,000	F
2	19 Mar 1975	24 m, off Del Monte Beach	Chert block	64,800	F
3	19 Sep 1975	11 m, off Del Monte Beach	Chert	1,200	F
4	20 Oct 1975	13 m, off Del Monte Beach	Chert	6,000	F
5	18 Nov 1975	52 m, off Cabrillo Point	Chert; Concr.	1,400	A
6	18 Nov 1975	56 m, off Fort Ord	Chert blocks	9,500	A
7	18 Nov 1975	22 m, off Del Monte Beach	Chert blocks	1,800	A
8	3 Mar 1976	11 m, off Del Monte Beach	Chert	5,400	F
9	18 May 1976	15 m, off Del Monte Beach	Concretions	82,500	A
10	10 Nov 1976	12 m, off Del Monte Beach	Chert; Concr.	9,800	F
11	6 Dec 1976	50 m, off Cannery Row	Chert; Concr.	6,500	F
12	7 Jan 1977	90 m, off Point Pinos	Chert	500	O
13	7 Jan 1977	150 m, Monterey Canyon	Gray Mud	—	
14	7 Jan 1977	140 m, Monterey Canyon	Concretions	600	F
15	25 Jan 1977	52 m, off Cabrillo Point	Chert; Concr.	9,300	A
16	9 Feb 1977	54 m, off Cabrillo Point	Chert block	6,400	A
17	9 Feb 1977	60 m, off Cabrillo Point	Chert; Concr.	4,200	A
18	10 Mar 1977	30 m, off Cannery Row	Chert	700	F
19	26 Apr 1977	15 m, off Del Monte Beach	Chert; Concr.	12,300	F
20	26 Apr 1977	25 m, off Del Monte Beach	Chert; Concr.	10,800	F
21	21 Jun 1977	55 m, off Lovers Point	Chert	8,400	A
22	4 Aug 1977	40 m, off Cannery Row	Concretions	14,800	F
23	8 Aug 1977	24 m, off Del Monte Beach	Chert; Concr.	7,500	A
24	11 Aug 1977	120 m, Monterey Canyon	Gravel; Mud	—	
25	27 Sep 1977	20 m, off Del Monte Beach	Chert; Concr.	2,900	F
26	28 Sep 1977	20 m, off Del Monte Beach	Concretion	250,000	A
27	1 Feb 1978	90 m, Monterey Canyon	Dark Mud	—	
28	1 Feb 1978	130 m, Monterey Canyon	Dark Mud	—	
29	1 Feb 1978	160 m, Monterey Canyon	Dark Mud		
30	3 Feb 1978	300 m, Monterey Canyon	Purisima	600	O
31	16 Feb 1978	7 m, off Capitola	Purisima	2,200	A
32	16 Feb 1978	10 m, off Capitola	Purisima	900	A
33	16 Feb 1978	7 m, off Soquel Point	Purisima	4,300	A
34	16 Feb 1978	7 m, off Point Santa Cruz	Mudstone	3,100	A
35	23 Feb 1978	7 m, off Point Santa Cruz	Chert	600	F
36	23 Feb 1978	7 m, off Natural Bridges	Mudstone	800	F
37	23 Feb 1978	8 m, off Terrace Point	Mudstone	700	F
38	10 Mar 1978	13 m, off Point Santa Cruz	Purisima	2,000	F
39	17 Jan 1979	15 m, off Del Monte Beach	Chert	2,200	F
40	1 Mar 1979	20 m, off Del Monte Beach	Chert	1,000	F

Explanation of Table I

In column under Substrate Sample, Concr. = Concretions
In columns under Relative abundance, Vacant bore holes, and Relative Abundance, Living borers,

A = abundant
F = few
O = none

	BORERS										NESTLERS				
Relative abundance, living borers	*Adula californiensis*	*Adula falcata*	*Lithophaga plumula*	*Chaceia ovoidea*	*Netastoma rostrata*	*Parapholas californica*	*Penitella conradi*	*Penitella gabbii*	*Penitella penita*	*Penitella fitchi*	*Crepidula perforans*	*Hiatella arctica*	*Irus lamellifer*	*Kellia laperousii*	*Petricola carditoides*
A		2	10		1		10	14				3			4
A		5	60	2	1	2	43	46	4		20	11	7	22	19
A			2		10		2	11	1		11			1	4
A					5		1	3			1	1			
F			2												
O															
A					1		1	8							
A		1	3		1	2	20	45	4		4	5	3	3	3
A			310	1		1	4	2			5		1	2	4
A			87				2	1	3		2			3	6
A			29		1	2	4	3			1	1			3
O															
O															
O															
O															
F								5							
O															
A			30				18	10	1				2		
A			2				5	7		1	7			5	
F								2							
A			19				8	2		1	5	1		3	
A			13	1	1		7	3		1					
A		1	8		3		12	17		1		12	1	5	6
A		2	28	3	2	24	25	22						10	6
O															
A	2	20	18						45		2	63		3	
O															
A	2	3	2		9		2	26	4		1	8		7	
A	1	17	6								1			2	
F								4	2						
F		2			1		4	7			2	12	1		
A	3				3			9	4			1	8	2	
A	1	17	6								1			3	
A			2				3	6			2		5	2	
F			1		2		4	3			2				5

mediately to determine if it had bore holes in it of biological origin and if any living or dead borers were present. All borers and a representative sample of the rock were then placed in fresh sea water and returned to the laboratory where the borers were identified, measured, and counted, then preserved along with a sample of the rock substrate from which they had come. If the dredge haul was large, the entire sample was returned to the laboratory where it was analyzed for borers.

In order to learn more about the type of stone penetrated by borers, representative samples of bored sedimentary rock recovered during this study were analyzed by thin section to determine their petrographic nature. In addition, CLARK (1978) subjected representative bored rock samples to carbonate analysis using a Leco W 12 Carbon Determinator (Model 761-100).

RESULTS

The following section will present results of (1) observations and collections made by shallow water diving on the Monterey shale off Del Monte Beach, (2) dredging operations, (3) intertidal work near Santa Cruz, and (4) carbonate and petrographic analyses of representative rock samples. In addition, observations on individual species of bivalve borers will be reviewed.

1. DIVING OBSERVATIONS ON MONTEREY SHALE OFF DEL MONTE BEACH

The paper by HADERLIE *et al.* (1974) included a review of all diving operations and observations made in the kelp bed off Del Monte Beach up to that time. Since then, additional diving work has been done to sample parts of the exposed shale bottom that had not been examined previously. Methods and techniques employed were the same as in the earlier studies.

The following species of bivalve borers have been found while diving on the shale outcrops of the Monterey Formation off Del Monte Beach: *Adula californiensis* (Philippi, 1847), *A. falcata* (Gould, 1851), *Lithophaga plumula* Hanley, 1843, *Barnea subtruncata* Sowerby, 1846, *Chaceia ovoidea* (Gould, 1851), *Netastoma rostrata* (Valenciennes, 1846), *Parapholas californica* (Conrad, 1837), *Penitella conradi* Valenciennes, 1846, *P. gabbii* (Tyron, 1863), *P. penita* (Conrad, 1837), and *Zirfaea pilsbryi* Lowe, 1931. In addition, the following molluscan nestlers have been found in vacant pholad holes: *Crepidula perforans* (Valenciennes, 1846), *Hiatella arctica* (Linnaeus, 1767), *Irus lamellifer* (Conrad, 1837), *Kellia laperousii* (Deshayes, 1839), and *Petricola carditoides* (Conrad, 1837). As will be pointed out below in the section on results from dredging, one additional species of pholad, *Penitella fitchi* Turner, 1955, was found in shale in slightly deeper water off Del Monte Beach.

Some of the borers listed above can readily be identified *in situ* by a diver, provided the animals are fairly large and the siphons are extended and exposed. These include *Barnea subtruncata, Chaceia avoidea, Parapholas californica,* and *Zirfae pilsbryi.* The siphons of all others are so small that, although they can be seen clearly projecting from a bored rock sample kept in an aquarium, they are exceedingly difficult to detect in the field under average diving conditions. The siphons tips of members of the genus *Penitella* can usually be distinguished from all other genera, but species determination in the field usually is impossible. Likewise, although the siphons of the mytilids *Adula californiensis, A. falcata,* and *Lithophaga plumula* are distinguishable from those of pholads, they are no sufficiently distinctive from species to species to allow for identification in the field.

Identification and attempts to quantify densities of populations of borers by observing the borers in place, while diving, is further hampered by shifting sand at the Del Monte Beach diving site. Along this beach there is considerable onshore-offshore sand movement with seasons. Following the first storm waves striking the beach in November and December each year much of the sand is combed off the beach and distributed in subtidal waters out to about 10 m depth. Sand covers much of the flat shale outcrops, sometimes up to 30 cm or more in thickness, for several months of the year. Yet, as will be pointed out later, some of the bivalve borers in the sale survive this seasonal burial. Others that cannot tolerate periodic burial are limited in distribution to the projecting ledges and ridges that remain sand-free throughout the year.

As part of this over-all study, BOOTH (1972) attempted to determine the distribution and density of boring bivalves that could be identified *in situ* along two transects running seaward for 500 m off Del Monte Beach. He found a discontinuous distribution of species along each transect, and considerable variation between the transects. BOOTH noted that *Parapholas* and *Zirfaea* were best able to tolerate periodic sediment cover and that *Chaceia* was most commonly found boring horizontally into shale ledges. Additional diving operations since 1972 have confirmed these observations. BOOTH was unable to detect *Adula, Barnea, Lithophaga,* or *Penitella* species in the deeper water along the transects he studied and concluded these borers were restricted to shallow water. In other areas off Del Monte Beach, we have not only made observations while diving, but have recovered shale samples by excavating the substrate and have found representatives of all these genera except *Barnea* out to far beyond the ends of BOOTH's transects. BOOTH also concluded that variations in hardness and carbonate content of the exposed Monterey shale were the major factors influencing the inhomogeneous distribution of bivalve borers along his transects. As will be pointed out below, however, recent dredging operations on the Del Monte Beach shale outcrops have allowed us to recover large blocks of Monterey Formation, particularly hard chert, and in this dense homogeneous rock we have found representatives of most of the genera of bivalve borers living side by side.

Additional details on observations made while diving on the shale beds of Del Monte Beach will be presented later in connection with comments on each species of boring bivalve.

2. DREDGING OPERATIONS

Table I summarizes the results of the dredging operations carried out over a 5-year period from March, 1974, to March, 1979. The 40 dredge hauls listed in Table I are those where a sample of the bottom was recovered successfully. Many more hauls, over 60 in fact, were made where the dredge came up empty. The general location of each haul is given in Table I and in Fig. 1. More precise data on the location of each dredge transect is on file in the Department of Oceanography, Naval Postgraduate School.

In the majority of the successful dredge hauls, sedimentary rock was recovered, but on most of the hauls made on the south wall of the Monterey Submarine Canyon only mud, clay, or gravel came up in the dredge. We made many other attempts to dredge rock from the canyon walls but collected no sample at all. This was a disappointment, for one of our objectives in this study was to sample the rocky wall of the canyon to determine if living stone borers were present and if they played a role in causing erosion and deeping of the canyon. In southern California, WARME, SCANLAND and MARSHALL (1971) found that *Parapholas californica, Netastoma rostrata, Adula californiensis,* and *Lithophaga plumula* bored intensely into the rocks of the rim and upper walls of the Scripps Submarine Canyon, and that in some areas these organisms were more important as eroders of rock than physical and chemical processes. Even though the walls of the Monterey Submarine Canyon are steep, it is apparent from our results that a sticky layer of clay covers most areas. GREENE (1977) succeeded in recovering rock samples from both the north and south walls of the Monterey Canyon. In some cases these were granite samples, in others siltstone or sandstone. Many of the non-granitic rocks recovered showed bore holes made by pholads and possibly mytilids, but no living borers were found. We must tentatively conclude, therefore, that living marine bivalve borers are not causing extensive erosion of the walls of the Monterey Canyon at the present time.

In the shallow water at the southern end of Monterey Bay, we were much more successful in recovering rock samples and living bivalve borers as is indicated in Table I. In some cases the chain bag dredge would come up with one large block of chert that had been broken off a ledge, or a large flat concretion broken out of a cherty matrix. In other cases, it picked up loose pieces of chert or rounded calcareous concretions that had been lying free on the bottom. Most samples collected off Del Monte Beach consisted of a mixture of these two rock types. The cherty material varied from exceedingly hard, flint-like rock to relatively soft siltstone. The concretions were rounded, irregular, or flattened boulders or slabs, but when broken apart all concretions regardless of external shape appeared to be of the same uniform type of hard calcareous rock.

In the shallow water off Santa Cruz relatively few dredge hauls were successful in recovering samples. In most cases the dredge would hang up on very hard outcrops, and when finally freed, came up empty. Off Capitola and Soquel Point a few successful hauls recovered samples from the Purisima Formation, and off the terraces to the west of Point Santa Cruz some samples of chert and mudstone were recovered.

When rock samples taken on a successful dredging expedition were returned to the laboratory for analysis, an attempt was made to quantify the amount of sample recovered. At first we measured the size of individual rocks recovered and weighed the entire sample, but this proved impractical, especially when the dredge was full of mixed rock samples of various sized fragments. Thus, in most cases, the physical dimensions of only the larger blocks of chert and larger concretions were determined. For the rest, the average volume of each sample was estimated.

After such measurements, all of the sample was carefully broken apart with a hammer and chisel and all living bivalve borers and nestlers were removed, identified, measured, counted, and preserved. The figures given in Table I in the columns of the various borers and nestlers are the total count of living animals of that species in the entire sample dredged. In some cases, the sample was small, consisting of one or two rock fragments; in other cases the sample consisted of a dredge nearly full of fragments, or one or two large blocks or boulders. Thus, the total number of borers recovered from each sample varied widely.

Large blocks of chert, broken off reefs, or large calcareous concretions, carried far greater numbers of borers than an equivalent weight or volume of small fragments or boulders. To give some idea of the maximum density of borers found in the subtidal rock outcrops off Del Monte Beach, a few of the dredged samples will be discussed in more detail.

Dredge Haul No. 2. The sample collected on this haul consisted of one block of uniform hard chert (hardness of 7 on the Mohs scale) that measured 60 × 36 × 30 cm. The rock had been broken off a reef and must have been projecting upward or outward into the water, for it had a rich growth of benthic organisms on all surfaces except at the break. This large chert block appeared to be typical of the substrate composing the elevated, ridge-like reefs under the kelp bed off Del Monte Beach, and probably carried a typical number of borers for the location and depth. As can be seen in Table I, this sample was bored by 8 different species of bivalves, and often by many individuals of each species. Most of the mytilids and pholads were mature, full-sized animals, a few were small and still in the boring stage. Most species penetrated only up to 10 cm or less into the block of chert, but the two *Chaceia ovoidea* and the two *Parapholas californica* were large animals and had penetrated up to 20 cm into the block.

This sample with its assortment of living borers demonstrated a phenomenon seen repeatedly throughout this study. The hard, uniform, siliceous, flint-like chert of the Monterey Formation is successfully bored by both mytilids and pholads living side by side, often with burrows in close contact. The mytilids have been considered chemical borers, yet the siliceous chert is not dissolved by acids and has extremely low carbonate content. The pholads have been considered mechanical borers, yet they penetrate chert that is much harder than their shell valves.

The relative numbers of the different species of *Penitella* from this sample is fairly typical of most subtidal samples examined. Previous reports (e.g. TURNER, 1955) have stated that *Penitella penita* is the most common pholad in the eastern Pacific. This is certainly true for the intertidal areas (see below under discussion of reefs at Santa Cruz), but subtidally in southern Monterey Bay, *P. penita* is relatively rare compared to *P. conradi* and *P. gabbii*, as can be seen from the data in Table I. Only in one subtidal sample, Dredge Haul No. 31, in shallow water off Capitola, was *P. penita* abundant and the others absent. The substrate sample, in this case, was from the Purisima Formation rather than chert.

Dredge Haul No. 9. The sample collected on this haul consisted of two large flattened calcareous concretions. One measured 50 × × 40 × 30 cm, the other 50 × 30 × 15 cm. Each block had been broken out of an exposed reef, and fouling growth was limited to one surface (assumed to be uppermost) indicating the blocks were lying flat on top of the reef. These large heavy concretions were penetrated by several species of pholads, but in small numbers of individuals. The one *Parapholas californica,* however, was a very large animal with a shell length of 12 cm and a burrow depth of 20 cm. The remarkable thing about this sample, however, was the great numbers of *Lithophaga plumula.* The upper surface of each block was crowded with large *Lithophaga* (50-60 mm average length, but up to 70 mm) in burrows side by side at right angles to the rock surface with only a thin lamella of stone between individuals. Typically, there were 8-10 individuals per 25 cm² of surface. Many of the larger *Lithophaga* had secreted smooth carbonate linings 4-5 mm thick on the walls of the burrows, particularly thick near the burrow opening. This lining appeared to be harder than the rocky substrate, for the rock had eroded back in many cases, leaving the tubular calcareous linings projecting above the rock surface similar to what is sometimes seen in the calcareous «chimnies» of *Parapholas californica.* These distinctive linings of *Lithophaga* burrows have also been reported from southern California by WARME and MARSHALL (1969).

Dredge Haul No. 26. The sample collected on this haul was a single large flat calcareous concretion which measured 100 × 50 × 50 cm. The sample had been broken off the top of a reef. This concretion was unusual in the great numbers of large living *Parapholas californica* it contained. Eighteen of these were in the post-boring stage and had shells averaging 14.0 cm long and 6.0 cm in diameter. These occupied burrows up to 30 cm deep. Six others, with shells 8-12 cm long, were still in the boring stage, and often had intersected the burrows of mature individuals. In no other sample recovered in this study have so many *Parapholas* been found, but diving operations off Del Monte Beach, where the distinctive siphons of *Parapholas* makes *in situ* identification possible, has shown that this species is widely distributed and often has the greatest population density of any pholad. Mature *Parapholas* often form calcareous tubes or «chimnies» which surround the siphons and line the walls of the outer part of the burrows. As the rocky substrate slowly erodes, these hard cement-like chimnies project 5 cm or more above the surface and provide a housing into which the siphons can be withdrawn. Diving observations indicate that *Parapholas* can tolerate a sand cover up to 15 cm deep over the reef and still project their siphon tips up into the water.

The large concretion recovered on Dredge Haul No. 26 also contained 3 large specimens of *Chaceia ovoidea.* Two of these were in the post-boring stage with a callum formed. Each had a shell length of 7 cm and a diameter of 4 cm. Each burrow was over 30 cm deep. The third specimen with a shell diameter of 2.5 cm was still in the boring stage and had excavated a burrow 15 cm deep.

Chaceia ovoidea, like *Parapholas,* was not often collected by dredging off Del Monte Beach. Diving observations have shown that these large, distinctive pholads are often abundant in the shale outcrops. Most of the *Chaceia* tend to drill horizontally into exposed ridges and ledges, but some distance down the flank of the ledge. This explains why so few are collected in the dredge, which normally breaks off the top of the ledge. *Chaceia* often severely undercuts ledges, and in many cases the bore holes are 60 cm or more deep. After the animal ceases to bore, it apparently lives for many years and the rock slowly erodes away from the surface, leaving the long white siphons dangling from what is left of the burrow.

General Comments on other Borers. We have collected two species of boring bivalves from subtidal shale off Del Monte Beach while diving, yet have never recovered either of them in dredged samples. *Zirfaea pilsbryi* is a large pholad commonly found boring into stiff clay or hard mud at Elkhorn Slough. Off Del Monte Beach, it is relatively abundant, occupying vertical burrows in the softer shale and mudstone. The distinctive siphons make identification easy. This species is often found in densities of 5 animals per m^2. *Zirfaea* excavate burrows up to 60 cm deep in the shale that forms the flat bottom between elevated reefs. Dredging is therefore unlikely to recover rock samples containing *Zirfaea.* Diving observations have indicated that large animals of this species can project their siphons up through as much as 30 cm of sand cover.

A second species not collected by dredging, *Barnea subtruncata,* is somewhat smaller than *Zirfaea.* It, too, has distinctive siphons and lives in soft flat shale off Del Monte Beach, but in numbers far fewer than *Zirfaea.*

Most of the boring bivalves found during this investigation had been collected earlier in Monterey Bay, and the subtidal shale off Del Monte Beach is the type locality for several species. One pholad, however, had never been collected north of southern California before (HADERLIE, 1979). *Penitella fitchi* was described from specimens collected from intertidal rock at Bahía San Bartolomé, Baja California. Additional recent specimens have been found at Redondo Beach, La Jolla, and San Diego. KENNEDY (1974) reported *P. fitchi* as a fossil in Pleistocene deposits from southern California and Baja California. During the present study, *P. fitchi* was found on four occasions. Single living animals were recovered on each of the dredge hauls numbers 20, 22 and 23. The animals were from 5.0 to 6.5 in shell length, were in the post-boring stage, and occupied burrows in hard chert. On Dredge Haul No. 25, a single set of valves (4.0 cm long) of a dead specimen was found in a burrow in chert.

To conclude these comments on borers collected from dredged rock, the sizes of some of the other bivalve borers not previously discussed will be mentioned. *Adula falcata* were found in only 4 of the dredge samples from southern Monterey Bay, but in most of the samples collected on the bottom at the northern edge of the Bay. The largest of these was 6.5 cm long, most were about 4 cm long. *Adula californiensis* were not found at all in dredged samples from southern Monterey Bay, but were present in small numbers in subtidal waters off Santa Cruz. *Netastoma rostrata* were usually less than 2 cm in length and were rarely abundant in any dredged rock. One individual, nearly 2 cm long, collected on 20 October 1975 from 13 m depth off Del Monte Beach released streams of white sperm while being examined in the laboratory. *Penitella conradi* has been considered to be a species that bores primarily into other mollusc shells, such as the abalone *Haliotis,* and only occasionally into clay or soft stone. In the subtidal Monterey shale deposits off Del Monte Beach, however, *P. conradi* is one of the most abundant borers in all kinds of natural rock, including the hardest chert. TURNER (1955) gave the maximum shell length of *P. conradi* as 3.3 cm. Many of the specimens collected from the chert recovered during this study were up to 5.0 cm in shell length (excluding siphonoplax). *P. gabbii* was about as abundant as *P. conradi* in most dredged samples. The largest *P. gabbii* was 6.0 cm long. *P. penita* was much less abundant in the subtidal shale off Monterey, but in the Purisima rock collected off Capitola, *P. penita* was common and the only member of the genus present. The largest individuals recovered were 6.0 cm in shell length (excluding siphonoplax).

One of the objectives of the dredging part of this study was to determine the bathymetric distribution of boring bivalves in Monterey Bay. As will be pointed out below, some species occur in the intertidal zone at Santa Cruz as high as 2 m above MLLW (mean lower low water or zero tidal level). Subtidally our dredging operations have shown (Table I) that living bivalve borers are common down to depths of 50 m in the southern part of the Bay. Below a depth of 50 m very few living animals have been found in recovered rock samples, although many rocks brought up from these deeper waters were riddled with burrows that were identical to those made by living pholads in shallower water. Many of the bored rock samples from deeper water had been broken off by the dredge, so these samples had not been transported to deeper water. Perhaps these bore holes were made by pholads in the past when the level of Monterey Bay was lower than at present, or when temperatures were different. The vacant holes do not appear to be geologically old, however, for they were not filled with compacted sediment and were often not even occupied by nestlers. Experiments now in progress (to be reported on later) have shown that very few boring bivalve larvae settle on or bore into experimental rock panels exposed in water depths exceeding 70 m in Monterey Bay.

3. Intertidal Reefs near Santa Cruz

One of the earliest reports of living bivalve borers in the intertidal zone at Santa Cruz was in the original edition of Ricketts and Calvin (1939). Ricketts had observed *Platydon cancellatus* (Conrad, 1837) in enormous numbers in banks of stiff blue clay and noted their erosive influence along the shore. He also found siphons of *Parapholas californica* projecting from rocky reefs in the intertidal zone at Santa Cruz, but the exact location of the reefs was unspecified. In this investigation we have concentrated on the rocky reefs in the area to the west of Point Santa Cruz and have not observed large numbers of living *Platydon* nor *Parapholas*. The few living *Platydon cancellatus* observed were nestlers in vacated pholad burrows. In the blocks of Purisima formation in the cliffs some 5 m above sea level at Santa Cruz, however, there are many Pliocene fossils of *P. cancellatus* to be seen as was reported by Addicott (1966).

Most of the results of the investigation being reported on here from the intertidal zone at Santa Cruz were included in a thesis by Clark (1978). This past year, studies have continued, particularly on the terraces west of Natural Bridges State Park.

On one large intertidal reef composed primarily of Monterey shale west of Point Santa Cruz, Clark found the following species of bivalve borers: *Adula californiensis, A. falcata, Lithophaga plumula, Netastoma rostrata, Penitella gabbii, P. penita,* and *Parapholas californica*. Of these, *Penitella penita* was by far the dominant species of borer and was found in rock ranging from the hardest chert to soft mudstone, from 0.7 to 2.0 m above MLLW, and in population densities of more than 10 mature individuals per 75 cm² surface area. Most individuals were found boring horizontally into ledges on the reef, particularly in pot holes where concretions had been displaced. Approximately half the *P. penita* were in the boring stage, half were mature with a fully-formed callum. The largest individuals had a shell length (exclusive of siphonoplax) of 5.7 cm.

The mytilid *Adula californiensis* was the second most common borer found on the reef at Santa Cruz. The largest of these had a shell length of 3 cm. All the other borers were present in much smaller numbers. Nestling bivalves occupying vacant pholad holes included *Semele rupricola* Dall, 1871, *Hiatella arctica, Protothaca staminea* Conrad, 1837, *Petricola carditoides, Kellia laperousii,* and *Platydon cancellatus*.

Clark (1978) also studied the borers in a transect across a flat, gently sloping terrace of chert and mudstone located west of Natural Bridges State Park. He found that here, too, *Penitella penita* was the dominant borer with *Adula californiensis, Penitella gabbii,* and *Netastoma rostrata* present in smaller numbers. The highest level where any of these occurred was at 1.0 m above MLLW where a few *Penitella penita* were found.

The broad, gently sloping terraces found between Natural Bridges State Park and Terrace Point are broken periodically by wide channels which cut through the terraces all the way up to the base of the sea cliff some 40 m shoreward from low water level. These channels have a floor of sand which varies in thickness throughout the year. Where these channels have cut through the terraces they have left vertical walls on each side, some 2 m or more high in some places. During this past year these exposed vertical sections of the terraces have been examined for stone borers. Shifting sand along the lower part of these walls erodes the rock very fast and many of the vertical walls are severely undercut. These regions harbor relatively few stone borers, mainly *Penitella penita* and *Netastoma rostrata,* and all individuals recovered were small and immature. It is possible that borers cannot survive long enough to reach maturity in this substrate being rapidly abraded by moving sand. In the vertical walls above the area of major sand movement, however, many *Penitella* borers were found and about half of these were large mature animals. *Penitella penita* again was the dominant species observed, but *P. gabbii* was also common. *Netastoma* *rostrata* and *Adula californiensis* were also present, but in small numbers. *Chaceia avoidea* was also found boring horizontally into these intertidal rock walls. FITCH (1952) reported *Chaceia* as being common at Santa Cruz, but CLARK (1978) did not observe this species during his work on the intertidal reefs and terraces. During this past year many specimens of *C. ovoidea* have been collected from the walls of the surge channels near Terrace Point at levels of 0.5 to 1.0 m above MLLW. All of the *Chaceia* so far observed have been small, up to 1.7 cm shell length, and in the immature boring stage, and no large *Chaceia* burrows have been seen, as re common in subtidal waters off Monterey. This would indicate that even the upper walls of the surge channels through these intertidal terraces erode away and expose the *Chaceia* before these long-lived borers become mature.

4. CARBONATE AND PETROGRAPHIC ANALYSES OF ROCK SAMPLES

The literature on rock boring organisms extends back for more than 200 years. Yet, many of the problems considered in these published studies and observations remain unresolved. At times in the past it has been fashionable to divide stone borers into two large categories, those that appear to dissolve the rock by chemical means, and those that abrade the rock mechanically. Among the bivalve borers, the mytilids, such as *Lithophaga* and *Adula*, have been considered chemical borers despite the fact there is no direct evidence to support the contention. Pholads as a whole have been considered to be mechanical borers, a conclusion based primarily on the functional morphology of these animals and their shells. The investigation being reported on here from Monterey Bay does not answer any of the lingering questions regarding the specific method or methods used by bivalves in burrowing into solid rock substrates. These studies have shown, however, that methods used for boring may be far more complex than we have suspected, and any one borer may be able to use a variety of methods of excavating burrows into various rocks having different physical and chemical properties. The fact that *Lithophaga plumula* (usually considered to be a chemical borer living primarily in calcium carbonate substrates) and various species of the genus *Penitella* (usually considered to be mechanical borers living primarily in soft rock) can live side by side and reach maximum size while boring into exceedingly hard, dense, siliceous chert in the shallow subtidal and intertidal zone of Monterey Bay, indicates that we have much to learn about the fundamental mechanisms of rock boring in marine animals.

The dominant rock types where living bivalve borers have been found in the present investigation in Monterey Bay fall into three main categories: (1) silty biogenic cherts and siliceous shales of the Monterey Formation, (2) calcareous concretions of various shapes and sizes associated with the chert beds or derived from them and lying free on the bottom, and (3) Purisima Formation dredged from shallow water at the north end of the Bay. We have attempted to learn something about the physical and chemical nature of these rocks into which many species of bivalves so regularly erode sizable burrows.

Both subtidally in the southern part of Monterey Bay and intertidally on the reefs at Santa Cruz, the basic Monterey Formation consists of organic mudstone, siltstone, siliceous shale, or chert, and in many areas all of these occur in one limited outcrop or reef. The hard, brittle chert is perhaps the most widespread and was most commonly recovered in dredge hauls. Representative samples of the Monterey Formation, both from the intertidal reefs at Santa Cruz, and from subtidal waters off Del Monte Beach have been analyzed for carbonates, and thin sections were prepared from which the U. S. Geological Survey made petrographic analyses.

The amount of $CaCO_3$ in any of the samples from the Monterey Formation (except for concretions), be they relatively soft mudstone or exceedingly hard chert, was extremely low, varying from 0.03 percent in some samples to a maximum of 0.74 percent in others. Analysis of thin sections of chert from the Santa Cruz reef showed it to be primarily (90-95 per cent) a ground mass of siliceous biogenic hash (radiolaria, sponge spicules, diatoms, etc.) with 5-8 percent clasts of silt-sized quartz, felspar, biotite, magnetite, hematite, and microcrystalline chert. No cementation was present. Some thin sections of the subtidal chert from off Del Monte Beach showed a similar composition to that just described with the addition of a few ghosts of calcareous foraminifera and some leached out siliceous tests. Other chert samples from off Del Monte Beach consisted of a ground mass of amorphous silica with clasts of silt-sized quartz, felspar, magnetite, and rare volcanic rock fragments along with some foraminifera fossils.

Chemical analysis of the concretions, both from the subtidal waters in Monterey Bay and from the reefs in the intertidal zone at Santa Cruz, gave a $CaCO_3$ content of 80-85 percent. Thin sections demonstrated that the concretions were recrystallized fossiliferous limestone with a ground mass of muddy carbonate now recrystallized to sparry calcite. The fossils were recrystallized foraminifera and siliceous tests replaced by calcite. In some samples, sand-sized clasts of quartz, felspar, and magnetite were present.

Neither chemical nor petrographic analyses were made on the Purisima Formation dredged from the northern part of Monterey Bay.

SUMMARY

1. This paper presents the results of a ten-year study on the distribution of bivalve molluscs that bore into rocky substrates in Monterey Bay.

2. Living borers were found in all types of sedimentary rocks from 2 m above MLLW to depths of over 50 m.

3. The Monterey shale exposed under the kelp beds in southern Monterey Bay has been examined by divers and 11 species of bivalve borers have been identified, including the mytilids *Adula falcata, A. californiensis, Lithophaga plumula,* and the pholads *Barnea subtruncata, Chaceia ovoidea, Netastoma rostrata, Parapholas californica, Penitella conradi, P. gabbii, P. Penita,* and *Zirfaea pilsbryi.*

4. Over 100 dredge hauls were made at various places in Monterey Bay from the shallow water off Santa Cruz to deep water in the Monterey Canyon. 40 of these hauls were successful in recovering a bottom sample. In water down to 50 m deep in the southern part of the Bay, rock samples recovered carried the same borers as were found in the diving operations, with the exceptions of *Adula californiensis, Barnea subtruncata,* and *Zirfaea pilsbryi.* In addition, the dredging recovered a species not previously reported from Monterey Bay, *Penitella fitchi.* Dredging in shallow water off Santa Cruz recovered samples of Purisima Formation with a variety of borers including *Adula californiensis.*

5. In deeper water of Monterey Bay, recovered rock samples showed evidence of bivalve borer activity, but no living borers were found.

6. Few samples of sedimentary rock were recovered from the walls of the Monterey Canyon and none carried living borers.

7. The intertidal reefs at Santa Cruz were populated, from low tide level to 2 m above MLLW, with *Adula californiensis, A. falcata, Lithophaga plumula, Chaceia ovoidea, Netastoma rostrata, Parapholas californica, Penitella gabbii* and *P. penita.* Of these, *Penitella penita* was the dominant species on these reefs.

8. Chemical and petrographic analyses of varios rock samples indicated that most of the bivalve borers in Monterey Bay bore into both siliceous rocks of various hardness and into calcareous rocks.

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MARINE FOULING DYNAMICS IN HAWAIIAN NEARSHORE ECOSYSTEMS: A SUGGESTED TECHNIQUE FOR COMPARISON AND EVALUATION

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USA

ABSTRACT

We have developed a technique for the rapid, quantitative assessment of marine fouling communities using test panels and a grid enumeration system. This technique measures quantitatively the frequency of selected organisms over the test panel surface. Field studies validating this technique were performed in two major Hawaiian estuaries, Pearl Harbor and Kaneohe Bay. Settlement data were collected for one, two and three month panel exposures at depths of one, three and five metres. Species-area curves were developed to determine minimum adequate panel size for experimental use. Monthly exposure replication throughout a period of one year enhanced statistical and facilitated the recognition of subtle changes in nearshore Hawaiian fouling assemblages.

Data from one month exposure intervals provided the most useful distinctions between harbor and depth variables. The analysis revealed that fouling assemblages in Pearl Harbor are considerably different from those observed in southern Kaneohe Bay. Pearl Harbor epifaunal settlement is dominated by the serpulid polychaete *(Hydroides elegans)*, the barnacle *(Balanus reticulatus)*, encrusting bryozoans *(Holoporella brunnea, Schizoporella serialis* and *Watersipora edmondsoni)*, the mollusks *(Vermetus alii, Ostrea* sp. and *Hiatella arctica)*, compound ascidians *(Botrylloides* spp.) and solitary ascidians. Southern Kaneohe Bay settlement is characterized by juvenile barnacles, *Balanus trigonus*, hydroids, erect bryozoans (such as *Aetea truncata*) and didemnid ascidian assemblages. Weight data collected from the test panel communities indicate that Pearl Harbor surface waters generally support a greater fouling biomass than does Kaneohe Bay.

Grid analyses of test panel communities exhibited an acceptable sensitivity to reliable pattern recognition. This technique was effective in terms of effort expended, exhibited a greater degree of precision than previously tested methods, could be performed by various laboratory personnel and provided data which could be realistically evaluated and related to operationally significant areas such as ship hull fouling.

INTRODUCTION

Marine fouling dynamics provide a useful means to evaluate the environmental condition of nearshore ecosystems. While the analysis of human impact on aquatic environments has been interpreted through chemical and physical water quality parameters, extrapolation to the functional, living ecosystem has often been difficult. The direct measurement of biological parameters provides a realistic approach to marine ecosystem assessment. Biotic measurements that reliably reflect the condition of the ecosystem are central to this theme. The ex-

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pensive task of monitoring an entire ecosystem is unnecessary when selected biotic assemblages are used to evaluate marine environmental conditions. Some advantages of using living systems are:

1) they are a direct measure of biological response;
2) they exist *in situ* without cost or maintenance;
3) they monitor continuously, integrating the effects of fluctuating environmental conditions, chronic low-level exposures, and acute perturbations;
4) they can be extremely sensitive through biological concentration;
5) they are a *direct* measure, requiring little instrumentation.

Often the objective of an assessment study is not only to characterize existing biota, but to evaluate the effects of environmental perturbations on particular ecosystem components through comparison and evaluation of similar biotic assemblages. Marine fouling organisms provide a useful means to evaluate nearshore environmental conditions. Recent studies in Hawaiian environments have used fouling panel assemblages to evaluate biotic response to sewage (RASTETTER and COOKE, 1979) nutrient enrichment (HENDERSON and SMITH, 1978), salinity variations (SMITH *et al.*, 1979) and the effects of power plant cooling water systems (GROVHOUG, 1979; McCAIN, 1975). A previous study (GROVHOUG, 1976) examined preliminary trends in settlement and distribution patterns at eight Hawaiian nearshore locations. The experimental design for the present study was derived from experience gained during the 1975-76 investigation.

The term «fouling biota» is used here to describe those organisms growing attached to submerged man-made structures such as internal and external shipboard surfaces, pilings, buoys, pipelines, etc. These organisms cost military and commercial interests millions of dollars annually, due to increased maintenance, cleaning and repair costs, reduced hull speeds, greater fuel consumption and lowered heat-transfer capacities in condenser systems (FISCHER *et al.*, 1975; TOWNSIN *et al.*, 1976). As an operational nuisance, fouling biota merit investigation and monitoring, however, certain other characteristics indicate their ability to accurately reflect general environmental conditions:

1) they are sessile and therefore, do not move from the study area these biota cannot avoid chronic or acute perturbations;
2) they are highly dependent on the water column (most of the community filters its food from the surrounding water and is dependent on the water column for respiration and dilution of waste products);
3) fouling is a universal phenomen and many fouling species are cosmopolitan in distribution;
4) life cycles of fouling organisms are sufficiently short-lived and respond to ambient conditions in a relatively rapid manner;
5) the community is readily sampled by exposing test panels.

Historically, marine fouling studies in Hawaii have been concerned with two operationally significant factors: 1) damage to wooden structures placed in the marine environment (KOFOID and MILLER, 1923; U.S. Navy Bureau of Yards and Docks, 1951; WALLOUR, 1959) and 2) shipboard fouling (VISSCHER, 1927, 1937 *a*, 1937 *b*; EDMONDSON, 1939, 1944; EDMONDSON and INGRAM, 1939). A review of these earlier studies with additional observations on fouling of naval mines, antitorpedo nets, buoys and test panel throughout the western Pacific (including Hawaii) comprised a summary report by HUTCHINS (1949). A comprehensive treatment describing marine fouling and its prevention was prepared for the Navy Department by Woods Hole Oceanographic Institution (1952). This report contains much information relevant to marine fouling dynamics in Hawaii. More recently, the U.S. Naval Oceanographic Office (NAVOCEANO) directed fouling studies off leeward Oahu and inside Pearl Harbor (LONG, 1969, 1970, 1972). Epifaunal (fouling) assemblages growing on pilings and other permanent, stationary structures were described for Pearl Harbor by EVANS *et al.* (1972, 1974), and for Kaneohe

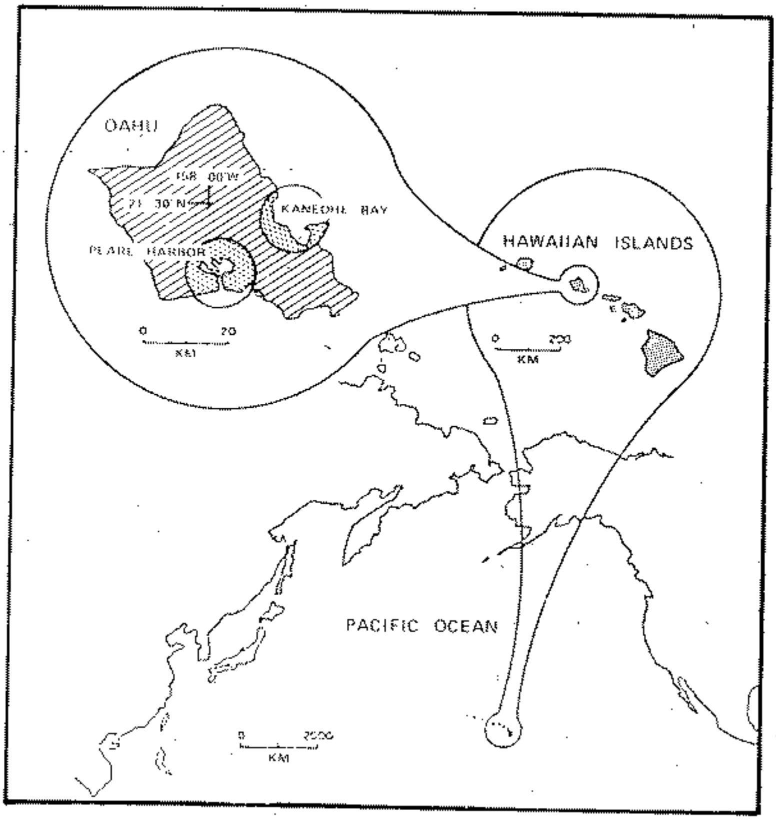

FIG. 1.—Pearl Harbor and Kaneohe Bay, Oahu, in perspective to the Pacific Basin.

Bay by BROCK (1976). The present study describes a technique that has been used to evaluate marine fouling dynamics in two Hawaiian estuaries.

STUDY SITES, MATERIALS AND METHODS

Study sites were located in the two major estuaries on the island of Oahu, Pearl Harbor and Kaneohe Bay (Fig. 1). During this study fouling data were collected from arrays suspended at Alpha Docks (21° 19' 57.5" N, 157° 58' 10" W) near the entrance to Pearl Harbor, and at the Kaneohe Marine Corps Air Station fuel pier (21° 26' 26.5" N, 157° 46' 05" W) located in southeastern Kaneohe Bay (Figure 2). Field data were collected during the period 27 April 1976-20 April 1977.

Asbestos test panels measuring 150 × 150 × × 3 mm were suspended at one, three and five metre depths from floats of each location (Figure 3). Three panels were suspended at each depth where the attachment to rectangular 910 × 300 × 6 mm plexiglass backing plates was made using 6.37 mm diameter nylon bolts through the center of each panel. Panels from each depth were retrieved and replaced with new panels at one, two and three month exposure intervals. Thus, data from twelve one-month panels, six two-month panels and four three-month panels were collected from each depth at each study site (for a total of 132 panels). During each panel removal sequence, the overlapping surfaces on plexiglass backing

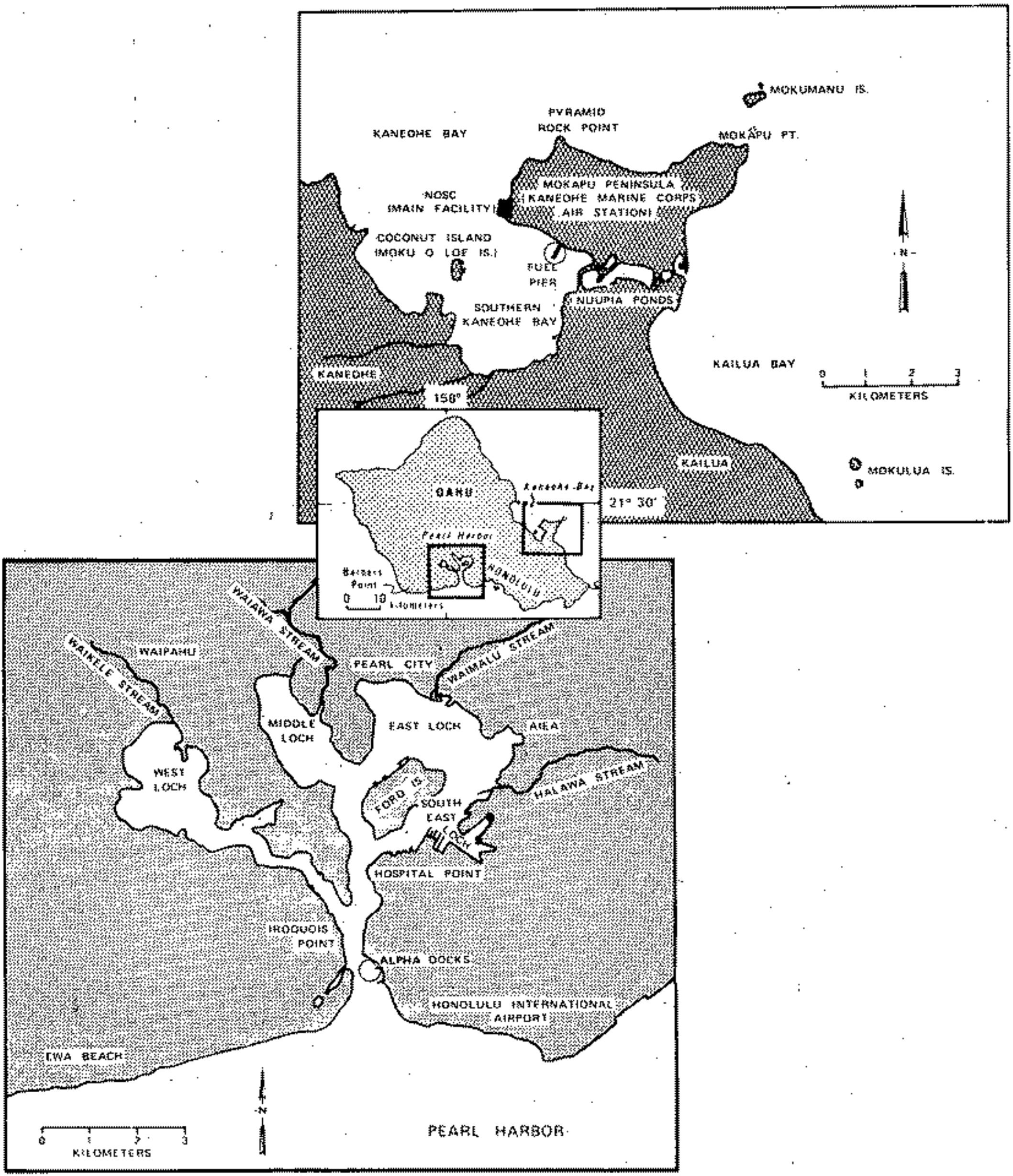

FIG. 2.—Locations of study sites in Pearl Harbor and Kaneohe Bay on the island of Oahu. Circles indicate study sites.

plates were scraped and brushed to remove extraneous fouling organisms (thus minimizing the edge effect of peripheral colonization).

Test panels were retrieved from field sites at predetermined intervals and transported to the laboratory in flat, covered plastic containers filled with seawater. In the laboratory excess fouling biota were carefully trimmed from the edges and back of each panel. Laboratory photographs were taken of each panel using a

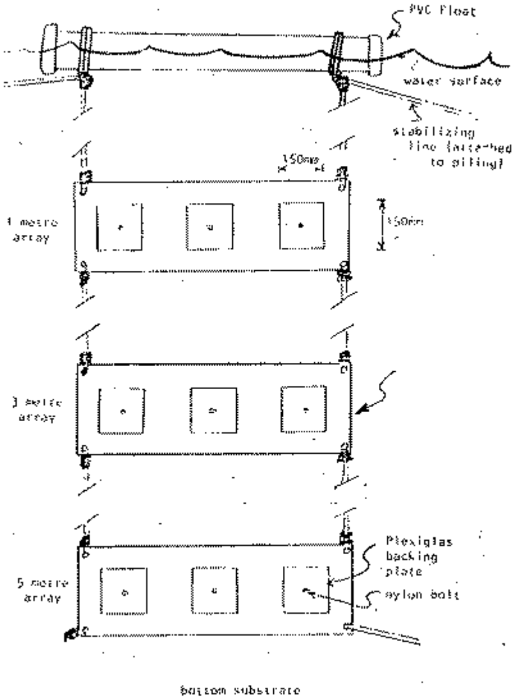

FIG. 3.—Sketch of fouling panel array configuration.

Nikon F, SLR camera (equipped with a 55 mm closeup lens); the light source was provided by two Honeywell (Model 202) synchronized strobe lights. Projected color slides were later viewed to evaluate detailed aspects of living panel biota. These photographs served as a permanent data record and often facilitated taxonomic identifications, when color and detailed morphology were diagnostic.

Wet and buoyant weights were next determined for test panels with living biota attached. The panels were then examined using a variable power (1X-7X) binocular dissecting microscope and an initial species list was compiled. After examination, the panels were placed in a refrigerator (at 4-5° C) overnight to permit slow relaxation of biota prior to fixation in 10 % seawater-buffered formalin the next day. By this relaxation technique many useful diagnostic characteristics were visible in fully expanded forms; when immediately preserved without relaxing, organisms such as polychaetes and tunicates severely contract, making identification difficult. After several days the panels were transferred into 70 % isopropyl alcohol. A second «wet» examination was made during this phase of laboratory analysis to verify completeness of the species checklist, determine selected species size ranges, estimate percent panel coverage, record dominance heirarchies and various other descriptive parameters. The panels were then air-dried to remove excess alcohol and oven-dried at 105° C for 48 hours. Final dry weights were determined and panels were stored until grid count analyses could be performed.

A series of four weight determinations were made for each panel: 1) initial dry weight of panel (oven-dried at 105° C for 48 hours) prior to field exposure, 2) «live wet» weight (after a 30-second vertical draining period to remove excess water), 3) «live buoyant» weight (to obtain a weight estimate of shell-forming versus non-shell-forming biota) and 4) final dry weight. Wet and buoyant weight regression equations were developed experimentally using twenty-five test panels to enable calculation of unfouled wet and buoyant weight values from initial dry weight data. The differences between the unfouled and the final fouled weights are referred to as Δ wet, Δ buoyant and Δ dry weight values. All dry and wet weights were determined using a Mettler (Model K7) laboratory balance. All buoyant weights were determined using an Ohaus (Model 311) triple-beam balance, by suspending panels in a large container of seawater (35 $^0/_{00}$ salinity, specific gravity: 1.025 @ @ 21.0° C). All weights were recorded to the nearest 0.01 gram.

In order to verify the optimal size for test panels, species-area curves (CAIN, 1938; RICE, 1967; RICE and KELTING, 1955) were determined for six 300 × 300 × 3 mm asbestos panels. These panels were exposed at each depth for one month at each study site. Curves were determined using a nested plot method with plots of 100, 900, 2,500, 4,900, 10,000, 22,500, 40,000 and 62,500 square millimetres centered on each panel using a template overlay system. Based on this species-area evaluation, test panels measuring 150 × 150 × 3 mm (containing 22,500 mm² surface area) were selected for this study (Fig. 4). To determine a reliable quantification scheme for quadrat size, a second experimental scheme was developed.

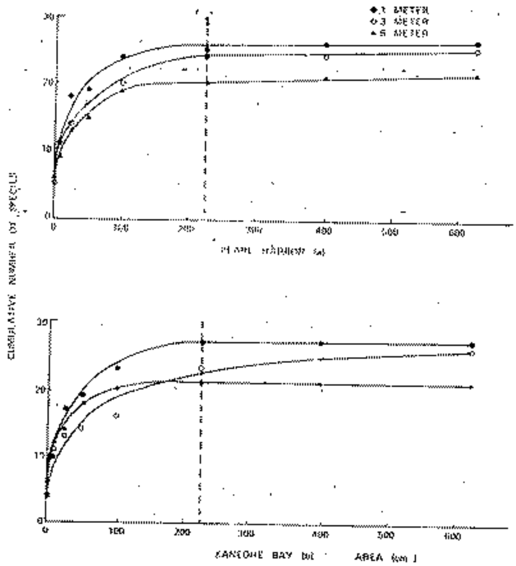

FIG. 4.—Species-area curves determined for Pearl Harbor and Kaneohe Bay fouling biota.

A sheet of graph paper measuring 300 × × 300 mm was used to model the planar area to be sampled. Square «individuals» (approximately ten square millimetres) were randomly placed on the paper. Thus, eighty-seven «individuals» produced about ten percent cover. As more «individuals» were sequentially added to the modeled field, the tendency for overlap increased. Therefore, the shapes of «individuals» were modified to non-square shapes. The areal size of each «individual» was maintained without producing overlap of those «individuals» already on the field. At each ten percent cover interval, the area was sampled using point and plot enumeration techniques. Plots here are considered square quadrats, which have been delineated in a regular grid pattern. Six different plot (quadrat) sizes were used: 25, 100, 225, 400, 625 and 900 square millimetres. Results of this sampling model are shown in Figure 5. Plot sampling tends to overestimate percent cover. The larger the plot the greater the over-estimation. Small changes in frequency near the upper end of the scale represent large changes in percent cover. However, the opposite is true at the other end of the curve (Fig. 6). Thus, for diverse communities where the dominant species do not occupy large percentages of the cover, plot frequencies represent a more sensitive measure of species quantities than point frequencies. If plot size is selected small enough that not more than one or two species show a frequency of 100 % (DAUBENMIRE, 1968), and also large enough such that one species does approach 100 % frequency, then the most sensitive frequency count for that community has been selected. For this study, plots (quadrats) measuring 5 × 5 mm were selected based upon the above considerations, size of individual organisms to be sampled and the intended use of this technique.

To determine the number of 5 × 5 mm quadrats required to adequately sample each panel, five species were selected which represent a range in size, abundance and dispersion patterns. Sequential counts of biota contained in 2 to 144 randomly selected quadrats were obtained from test panels exposed in Pearl Harbor and Kaneohe Bay. These data were plotted for selected species. All curves tended to stabilize at between 75 and 90 quadrats. However, to enhance statistical validity, 100 quadrats were selected for frequency determinations on each panel during this study.

Grid count analyses were performed to provide frequency determinations of common foul-

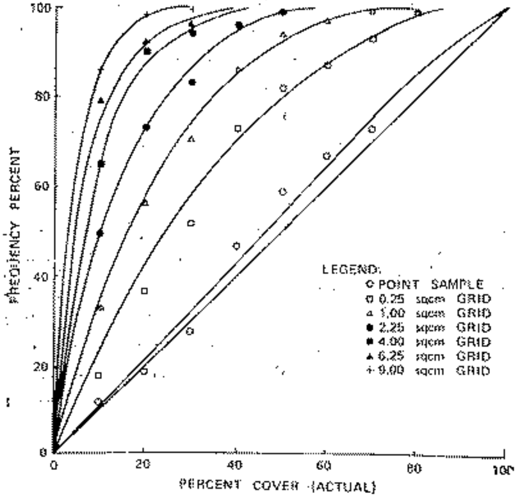

FIG. 5.—Comparison of point and plot frequency sampling and the effect on percent cover and percent frequency.

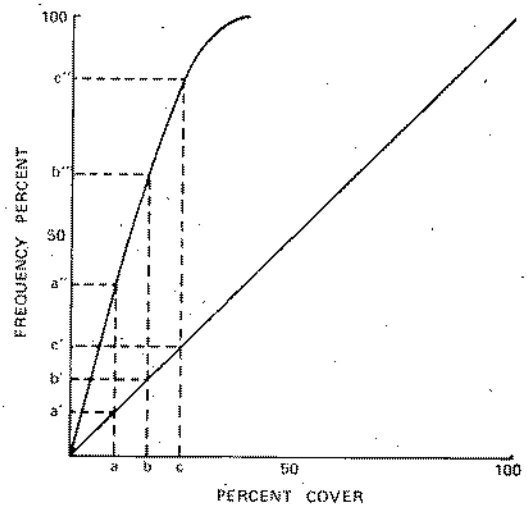

FIG. 6.—Sensitivities of point and plot sampling to percent cover and percent frequency. The plot sampling curve was selected such that not more than one or two species have frequencies of 100 % and at least one species approaches 100 % frequency. In this case the plot frequency measure is more sensitive to differences at lower percent cover than is a point frequency measure. (c''-b'') in greater than (c'-b'). (b''-a'') is greater than (b'-a').

ing biota. Since frequency is a measure of the probability of encountering a particular taxa in a certain size quadrat, one hundred 5 × × 5 mm quadrats were etched in a regular pattern on a 150 × 150 mm plexiglass overlay. Using this overlay to analyze each panel, percent frequencies were recorded for each selected taxa. For example, if one or more barnacles were present in 45 of the one hundred quadrats, this taxa received a frequency of 45 percent. An organism was recorded «present» if any part of the animal overlapped into the quadrat. These counts were performed on dried panel biota. Most taxa could be recognized, identified and enumerated in a dried condition. Those few minor groups that could not were omitted from analytical consideration. Frequency counts were found to be less time-consuming and more reliable than counts of individuals during this analysis.

To select a useful analytical technique for these frequency data, several classification techniques were reviewed (Clifford and Stephenson, 1975; Green, 1971, 1974; Mueller-Dombois and Ellenberg, 1974; Orloci, 1967; Pielou, 1977; Preston, 1948, 1962 *a*, 1962 *b*; Sneath and Sokal, 1973). Orloci (1967) describes an agglomerative polythetic method where distance is used to cluster vegetation stands into classes prior to a principal components analysis. We've selected Orloci's sum of squares techniques as an appropriate method of analysis for a portion of our data.

Test panels can be viewed as points in p dimensional space, where p is the number of species being considered in the analysis. The distance between points can be used in a comparison of the panels. If $X_{i,j}$ is the frequency measure of species i on panel j, then the distance between panels j and k is calculated as:

$$D_{j,k} = \sqrt{\left(\sum_{i=1}^{p} (X_{i,j} - X_{i,k})^2\right)}$$

As a comparison between classes Orloci (1967) suggests using the average between group distance,

$$\overline{D}_{m,n} = \frac{\sum_{j=1}^{s_m} \sum_{k=1}^{s_n} D_{j,k_k}}{s_m s_n}$$

where s_m and s_n are the number of panels in the two classes, m and n. Orloci uses both the absolute distance defined above and an alternative «standardized distance». Since «standardized distances» tend to under-represent differences between panels, if those differences are unidimensional, only absolute (Euclidean) distances were used in these analyses.

The objective of the analytical technique developed in this paper is to determine if two previously identified classes of panels are statistically distinct on the basis of community structure. A test was developed to determine if $\overline{D}_{m,n}$ is sufficiently large to justify separation. The expected value of $\overline{D}_{m,n}$, if the two groups are not distinct, can be estimated by the average within-group distance:

$$\overline{D}_{in} = \frac{\sum_{j=1}^{s_m - 1} \sum_{h=j+1}^{s_m} D_{j,h} + \sum_{k=1}^{s_n - 1} \sum_{g=k+1}^{s_n} D_{k,g}}{s_m(s_m - 1)/2 + s_n(s_n - 1)/2}$$

Therefore, the hypothesis, H_o: $\overline{D}_{m,n} \leq \overline{D}_{in}$, can be tested using a Student's «t» test.

Classes were also compared using «t» tests on the mean frequency of each species and mean weight data. For all comparisons, the one, two and three month exposure panels were considered separately. No attempt was made to reduce the noise due to seasonality by month to month pairing of samples for the «t» tests and sample means. These tests were compared to the results of the distance test, which does not lend itself to pairing. Additionally, correlations were performed between species frequencies and weight data.

RESULTS

During this investigation more than ninety different invertebrate taxa were identified from test panels exposed in Hawaiian nearshore environments (Table 1). Certain biota clearly dominate the fouling assemblages in Pearl Harbor and Kaneohe Bay, both in numbers and biomass. The numerical dominance evident on one month panels is often maintained by the same biota for longer term (three month) intervals. Qualitative comparisons between panel fauna and adjacent piling biota at each study site indicate that fouling assemblages in both estuarine environments approached a stable stage of community development within three months.

Data from thirty selected categories of taxa were analyzed to evaluate spatial and temporal settlement patterns. Table 2 summarizes the results of comparisons and correlations for one, two and three month exposure data. The following class comparisons were made: 1) Kaneohe Bay, all depths vs. Pear Harbor, all depths; 2) Kaneohe Bay, one metre vs. Kaneohe Bay, three metres; 3) Kaneohe Bay, three metres vs. Kaneohe Bay, five metres; 4) Pearl Harbor, one metre vs. Pearl Harbor, three metres; and 5) Pearl Harbor, three metres vs. Pearl Harbor, five metres. Correlations between species and total panel weight data were also performed. The one, two and three month exposure data were considered separately for all comparisons and correlations. The various symbols used in Table 2 signify confidence levels of «t» tests and correlations. For example, «X» signifies that the correlation coefficient is significantly greater than zero (> .8), while a negative sign «—*» indicates that the correlation coefficient is significantly less than zero (< .8). An «X» indicates that the correlation coefficient is moderately different (i.e. > .5 to .8 or < —.5 to —.8). Single characters indicate a 95 % confidence limit and double characters indicate a 99 % confidence limit. The following symbols in the comparison columns (Table 2) indicate which of the two classes possesses the higher mean: P = Pearl Harbor, K = Kaneohe Bay, S = shallow and D = deep. Thus «SS» in a column signifies that the shallower depth in the comparison had a significantly higher mean with 99 % confidence; «K» in a column indicates that Kaneohe Bay had a higher mean than Pearl Harbor with 95 % confidence.

Sixteen taxa show distinct separations between locations (harbors). Spirorbinae, *Balanus reticulatus, Vermetus alii, Ostrea* sp., *Hiatella arctica, Holoporella brunnea, Schizoporella serialis, Watersipora edmondsoni,* and solitary ascidians represent nine taxa with significantly higher sample means for the Pearl Harbor station. Hydrozoa, *Balanus trigonus,* juvenile *Balanus, Aetea truncata, Microporella ciliata, Diplosoma macdonaldi* and colonial didemnid ascidians are seven groups which are significantly characteristic of southern Kaneohe Bay fouling assemblages. All these categories demonstrate significantly different sample means at the 99 % confidence limit. Additionally, the distance comparisons between harbors are significant well above the 99 % level for one, two and three month exposure intervals.

Weight correlations reflect two general groupings. Those early settling taxa which are small, light-bodied forms such as folliculinids, Hydrozoa, Spirorbinae, juvenile *Balanus, Aetea truncata* and *Schizoporella serialis* showed strong negative correlations with respect to wet, buoyant and dry panel weights. Taxa in this grouping are more easily outcompeted by other, more resilient forms. These heavier-bodied, faster-growing, often larger and more dominant biota such as soft-tube polychaetes, *Balanus reticulatus,* colonial didemnid ascidians, *Botrylloides* spp. and solitary ascidians were positively correlated with overall panel weights.

Depth comparisons (classes 2-4 in Table 2)

TABLE 1

CHECKLIST OF SPECIES ENCOUNTERED ON TEST PANELS EXPOSED IN PEARL HARBOR AND KANEOHE BAY, OAHU DURING THE PERIOD APRIL, 1976-APRIL 1977

Taxonomic Hierarchy	*Genus/Species*	*Naming Authority/Date*	*HCZDB #*
Chlorophyta (green algae)			
Chlorophyceae			
Ulotricales/Ulvaceae			
	Ulva fasciata	Delile, 1813	0413160201
Protozoa (protozoans)			
Sarcodina			
Granuloreticulosa			
	Foraminifera, several unidentified spp.		1852000000
Ciliata			
Spirotricha/Folliculinidae			
	Parafolliculina violaceae	(Girard, 1888)	1922010101
	Metafolliculina andrewsi	Hadzi, 1951	1922010201
Peritricha			
	Zoothamnium sp.		1923XXXXXX
Porifera (sponges)			
Calcarea			
Homocoela			
	several unidentified spp.		3511000000
Demospongiae			
	several unidentified spp.		3520000000
Hadromerida			
	Terpios zeteki	(de Laubenfels, 1936)	3527010101
Cnidaria (coelenterates)			
Hydrozoa			
Hydroida			
	Garveia humilis	(Allman, 1877)	3711070101
	Turritopsis nutricula	(McCrady, 1856)	3711100301
	Clytia hemisphaerica	(Linnaeus, 1767)	3711200101
	Obelia dichotoma	(Linnaeus, 1758)	3711200201
Anthozoa/Zoantharia			
Actinaria/Aiptaisiidae			
	Aiptasia pulchella	Carlgren, 1943	3742340101

TABLE I (Continued)

Taxonomic Hierarchy	*Genus/Species*	*Naming Authority/Date*	*HCZDB #*
Platyhelminthes (flatworms)			
Turbellaria			
	several unidentifies spp.		4130000000
Nematoda (roundworms)			
	several unidentified spp.		5100000000
Entoprocta (nodding heads)			
Loxosomatidae			
	Loxosoma sp.		5311010201
Pedicellinidae			
	Barentsia gracilis	(M. Sars, 1835)	5311060201
Annelida (segmented worms)			
Polychaeta			
Erratia/Spintheridae			
	Spinther japonicus	Imajima & Hartman, 1964	551103XXXX
/Phyllodocidae			
	unidentified phyllodocid		5511060000
/Syllidae			
	Trypanosyllis zebra	(Grube, 1860)	5511140301
	Myrianida crassicirrata	Hartman-Schroder, 1965	5511147601
Sedentaria/Spionidae			
	Pseudopolydora pulchra	(Carazzi, 1895)	55210102XX
	unidentified spionid		5521010000
/Cirratulidae			
	Cirriformia puntata	(Grube, 1859)	5521040204
/Chaetopteridae			
	Phyllochaetopterus verrili	Treadwell, 1943	5521070102
	Chaetopterus variopedatus	Renier, 1804	5521070201
/Terebellidae			
	Thelepus setosus	(Quatrefages, 1865)	5521225002
/Sabellidae			
	Branchiomma cingulata	(Grube, 1870)	5521230105
	Demonax leucaspis	(Kinberg, 1867)	5521230302
	Sabellastarte sanctijosephi	(Gravier, 1906)	552123XXXX
/Serpulidae/Spirorbinae			
	Pileolaria pseudomilitaris	(Thiriot-Quievreux, 1965)	5521240202

TABLE 1 (Continued)

Taxonomic Hierarchy *Genus/Species* *Naming Authority/Date*	*HCZDB #*
Janua pseudocorrugata (Bush, 1904)	5521240302
Janua stueri Sterzinger, 1909	5521240302
/Serpulidae/Serpulinae	
Hydroides elegans (Haswell, 1883)	5521244201
(=*H. novegica* Gunnerus, 1768)	
Hydroides lunulifera Claparede, 1868	5521244204
Pomatoleios kraussi (Baird, 1865)	5521244701
/Serpulidae/Filograninae	
Filograna implexa Berkeley, 1835	5521248001
(=*Salmacina dysteri* (Huxley, 1855))	
Arthropoda (arthropods)	
Pycnogonida	
Phoxichilidiidae	
Anoplodactylus portus Calman, 1927	6391010402
Crustacea	
Cirripedia/Balanidae	
Balanus amphitrite amphitrite Darwin, 1854	6451090101
Balanus eburneus Gould, 1841	6451090103
Balanus trigonus Darwin, 1854	6451090106
Balanus reticulatus Utinomi, 1967	6451090107
Malacostraca/Isopoda	
Mesanthura hieroglyphica Miller & Menzies, 1952	6471060201
Cirolana sp.	6471160100
Sphaeroma walkeri Stebbing, 1905	6471220101
Paracerceis sculpta (Holmes, 1909)	6471220201
Muuna acarina Miller, 1941	6471320101
Crustacea	
Malacostraca/Amphipoda/Corophiidae	
Corophium baconi Shoemaker, 1934	6473180101
Ericthonius brasiliensis Dana, 1852	6473180201
/Amphipoda/Gammaridae	
Elasmopus hawaiiensis Barnard, 1979	6473250203
/Amphipoda/Caprellidae	
Paracaprella pusilla Mayer, 1890	647501XXXX
Malacostraca/Decapoda/Reptantia/Portunidae	
Thalamita integra Dana, 1852	6488313301
/Decapoda/Reptantia/Xanthidae	

TABLE 1 (Continued)

Taxonomic Hierarchy	*Genus/Species*	*Naming Authority/Date*	*HCZDB #*
	Pilumnus oahuensis	Edmondson, 1931	6488335806
Stomatopoda/Squillidae			
	Gonodactylus falcatus	(Forskal, 1775)	6489010201
Mollusca (mollusks)			
Gastropoda			
Mesogastropoda/Vermetidae			
	Petaloconchus keenae	Hadfield & Kay, 1972	7022430201
	Vermetus alii	Hadfield & Kay, 1972	7022430401
Mesogastropoda/Calyptraeidae			
	Crucibulum spinosum	(Sowerby, 1824)	7022750101
	Crepidula aculeata	Gmelin, 1791	7022750201
Bivalvia			
Mytiloida/Mytilidae			
	Brachidontes crebristriatus	(Conrad, 1937)	7054010301
Pteroida/Pteriidae			
	Pinctada radiata	Leach, 1814	7055010102
/Ostreidae			
	Ostrea hanleyana	Sowerby, 1871	7055060203
/Anomiidae			
	Anomia nobilis	Reeve, 1859	7055200101
Myoida/Hiatellidae			
	Hiatella arctica	(Linnaeus, 1767)	7057100101
Ectoprocta (bryozoans)			
Gymnolaemata			
Ctenostomata/Vesiculariidae			
	Amathia distans	Busk, 1886	7511010101
	Amathia vidovici?	(Heller, 1867)	7511010102
	Bowerbankia gracilis	Leidy, 1855	7511010302
Cheilostomata/Aeteidae			
	Aetea truncata	(Landsborough, 1852)	7513010101
/Bicellariellidae			
	Bugula neritina	(Linnaeus, 1758)	7513060101
	Bugula californica	Robertson, 1905	7513060102
/Smittinidae			
	Savignella lafonti	(Audouin, 1826)	7513510201
	Hippopodina feegeensis	(Busk, 1884)	7513510301

TABLE 1 (Continued)

Taxonomic Hierarchy	*Genus/Species*	*Naming Authority/Date*	*HCZDB #*
	Holoporella aperta	(Hincks, 1882)	75135104XX
	Holoporella brunnea	(Hincks, 1884)	75135104XX
	Parasmittina sp.		7513510500
Gymnolaemata			
Cheilostomata/Schizoporellidae			
	Schizoporella serialis	(Heller, 1867)	7513520101
/Cheiloporinidae			
	Watersipora edmondsoni	Soule & Soule, 1868	7513540602
/Microporellidae			
	Microporella ciliata	(Pallas, 1766)	7513620101
Echinodermata (spiny-skinned animals)			
Ophiuroidea			
Gnathophiurida/Ophiactidae			
	Ophiactis sp.		7841010100
Chordata			
Urochordata (tunicates & sea squirts)			
Ascidiacea/Enterogona			
	Perophora sp.		8311010100
	Ciona intestinalis	(Linnaeus, 1767)	8311030101
	Ascidia sidneiensis	Stimson, 1855	8311040102
	Ascidia interrupta	Heller, 1878	8311040102
	Trididemnum savignii	(Herdman, 1886)	8311120102
	Didemnum edmondsoni	Eldredge, 1966	8311120303
	Didemnum candidum	Savigny, 1816	8311120305
	Diplosoma macdonaldi	Herdman, 1886	8311120402
	Polyclinum spp. (2)		8311130200
/Pleurogona			
	Symplegma connectans	Tokioka, 1949	8312010101
	Botryloides spp. (3)		831201XXXX
	Styela partita	(Stimson, 1852)	8312020102
	Microcosmus exasperatus	Heller, 1878	8312030101
	Herdmania momus	(Savigny, 1816)	8312030201

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* HCZDB# refers to the computer address identification number assigned for each taxa listed; the Hawaii Coastal Zone Data Bank maintains a comprehensive listing of organisms inhabiting the northeast Pacific Basin; "X's" indicate that a number has not yet been assigned for a specific taxa; ending "O's" indicate the level to which identification has been performed (e.g. a number ending in "00" indicates a generic identification only).

TABLE 2

A SUMMARY OF SIGNIFICANT COMPARISONS ("t" TESTS) AND CORRELATIONS (r) OF FOULING SPECIES DATA WITH LOCATION DEPTH AND WEIGHT VARIABLES

Comparisons 1-5 are described in the text (1 = harbor separation, locations; 1-4 = depth comparisons). Correlations are for species vs. wet, buoyant and dry weight data. Legend: a = 1 month exposure, b = 2 month exposure, c = 3 month exposure, P = Pearl Harbor, K = Kaneohe Bay, S = shallow, D = deep, X = r of > ± .5 to ± .8, * = r of > ± .8, single characters = 95 % confidence limits, double characters = 99 % confidence limits.

	COMPARISONS															CORRELATIONS								
	1			2			3			4			5			Wet			Buoyant			Dry		
Category	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*
Folliculinidae (2 spp.)										S						-XX	-**	-X	-XX	-XX	-X	-X		-X
Porifera (several spp.)		P	P							D														
Hydrozoa (several spp.)	KK		K																		XX			XX
Soft-tube polychaetes	K															X	XX					X	X	
Spirorbinae (3 spp.)	PP	PP	P													-XX	-XX	-X				-X		
Hydroides (2 spp.)			P										S			X						X		
Balanus eburneus																					X		X	X
B. reticulatus	PP	PP		S									S			XX			XX			XX		X
B. trigonus	KK	KK	KK																					
Juvenile *Balanus*	KK	KK	K	D															-X	-X	-XX	-X	-X	-X
Erichthonius brasiliensis	P	P																						
Petaloconchus keenae																-XX			-X					

Vermetus alii	PP	PP	PP																					
Ostrea sp.	PP	PP	PP							S				D										
Hiatella hawaiensis		P	PP									D												
Amathia sp.																		X						
Aetea truncata	KK																		-XX	-X			-X	
Bugula neritina				SS						S						XX		X				X		
B. californica																X	-XX					X		
Savignella lafonti		P														XX			XX			XX	X	
Holoporella aperta							D						D	D					-X		-X			
H. brunnea	PP	PP	PP														-XX	-X	-X		-X	-X		
Schizoporella serialis ...	PP																							
Watersipora edmondsoni	PP		PP																					
Microporella ciliata ...	KK																							
Diplosoma macdonaldi.	KK	KK																						
Colonial didemnid ascidians (3 spp., exl. *D. macdonaldi*)	KK	KK	KK	S						S			S			XX	XX			X			X	
Symplegma connectans.	K		P							S														
Botryloides (3 spp.) ...	P	P	P							S			S			XX	XX		**	XX		**	XX	
Solitary ascidians (3 spp.)		P	PP													**	XX	X		XX	XX	**	XX	XX
Δ wet weight						S				S			SS											
Δ buoyant weight													S											
Δ dry weight	P												SS		S									
Distance (see text)	**	**	**	*																				

show fewer consistent patterns. Certain taxa such as *Bugula neritina, Balanus reticulatus, Ostrea* sp. and colonial didemnid ascidians exhibit significantly higher means for shallow depths. Data for other taxa such as *Holoporella aperta, Hiatella arctica,* juvenile *Balanus* and Hydrozoa indicate a preference for the deeper arrays used in the comparison. One species, *Holoporella aperta* consistently demonstrated a preference for deeper water environments, especially in Pearl Harbor.

Data from one month exposures consistently represented more significant comparisions and correlations for both species and weight parameters. Two and three month data contained about half as many significant separation statistics when compared with one month exposures.

DISCUSSION

Results for the five comparisons and correlations of species to weight and distance data (Table 2) reflect the usefulness of the suggested technique. Statistically significant separation of classes (locations, depths and weights) has been demonstrated. The differences between classes can be detected at three levels, each reflecting a separate measure of biological response to environmental conditions. The distance measure indicates general (cumulative) differences between classes. The sum of many specific differences (such as species presence-absence, frequency, weight, location, depth, etc.) are incorporated into the distance value. Individual taxa reflect other specific differences in the data matrix relating to growth rates, size, etc. Weight data provide a third level of separation which reflect the general productivity of the area under study.

In Pearl Harbor and Kaneohe Bay the fouling assemblages are influenced by various environmental factors such as, elevated nutrients, weak circulation patterns, freshwater dilution, various pollutants, shipborne biotic introductions, predation, competition, etc. However, as expected in a semitropical region, relatively stable annual settlement and development patterns were observed during this study. Characteristic harbor fouling biota were analyzed and differentiated for each estuary. Many of these selected organisms are world-wide in distribution and, therefore, have a potential application for future comparative studies. Several species identical to those in our study were listed by Boyd (1972) who performed a detailed study of the fouling community structure and development in Bodega Bay, California. Mook (1972) lists nine genera (and several species) identical to those inhabiting Hawaiian estuaries. He studies fouling invertebrates in the Indian River estuary in western Florida and, incidentally, also uses 150 × × 150 mm panels determined from species-area studies, Likewise, Sutherland and Karlson (1977) reporting fouling data from Beaufort, North Carolina, and Osman (1977) reporting fouling data from Woods Hole, Massachusetts list many of the same fouling species as those reported during our study.

The potential utility of the marine fouling community as a field monitoring technique was discussed by Fischer (1974). He suggested that cooperative marine fouling studies in widespread and geographically diverse estuarine environments be considered using carefully selected taxa and comparable analytical techniques. The technique described in the present paper represents an attempt to further develop a portion of this concept. A method for reliable quantification, whether applied to environmental assessment studies or investigations of ship hull fouling is a necessary component of marine fouling research.

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NEW MARINE INDUSTRY APPLICATIONS FOR CORROSION AND BIOFOULING RESISTANT, COPPER-NICKEL ALLOYS

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SYNOPSIS

The sea water corrosion and biofouling resistance of 90/10 copper-nickel is reviewed in relation to new applications for the alloy in marine based industries. Copper-nickel in the form of expanded metal mesh, for fish cages, shellfish trays and sea water intake screens, is shown to offer both practical and economic advantages for existing systems as well as provide a viable basis for new, innovative engineering concepts. The lining of sea water intake ducts and the sheathing of offshore structures are examples of other new application developments in which the alloy offers an economic means of overcoming difficult and expensive maintenance problems. The cladding of ships' hulls with copper-nickel has been developed over the last decade. The construction and performance of copper-nickel hulled vessels are described, and their advantages in terms of significantly reduced fuel consumption and dry dock maintenance, assessed.

1. INTRODUCTION

The sea is an old adversary and a continuous challenge to man's endeavours to exploit the oceans. The urgent need to develop the ocean's mineral, food and energy resources, to reduce the maintenance and fuel costs of ships, have brought new problems for corrosion resistant materials to overcome.

The sea is a hostile and demanding environment, corrosive to most metals and producing equally rapid degradation of plastics. Marine organism settlements foul surfaces. Storms make heavy demands on structural strength and integrity, and maintenance of offshore structures is difficult, expensive and sometimes impossible.

Copper and copper alloys have a long and successful history of use in marine applications. Copper cladding of wooden hulled warships was introduced by the Royal Navy as long ago as 1761. The copper cladding was intended to prevent wood boring organisms from damaging the hull but it was soon noticed that copper offered an even more important advantage in discouraging the settlement of marine organisms on the surface.

Copper alloys offer improved strength, erosion and corrosion resistance, and providing the alloy contains at least 70 % copper, they retain the anti-fouling characteristics exhibited by copper itself. One family of copper alloys offering an outstanding combination of strength, sea water corrosion and biofouling resistance are the copper-nickel alloys containing 5 to 30 % nickel and small additions of iron. Originally developed as heat exchanger tube materials for ship and coastal power station condensers, their corrosion and anti-fouling behaviour has been tested and proven over many years of service. The 90/10 copper-nickel alloy in particular has now gained wide acceptance for desalination plant, and offshore platform sea water piping and is rapidly estab-

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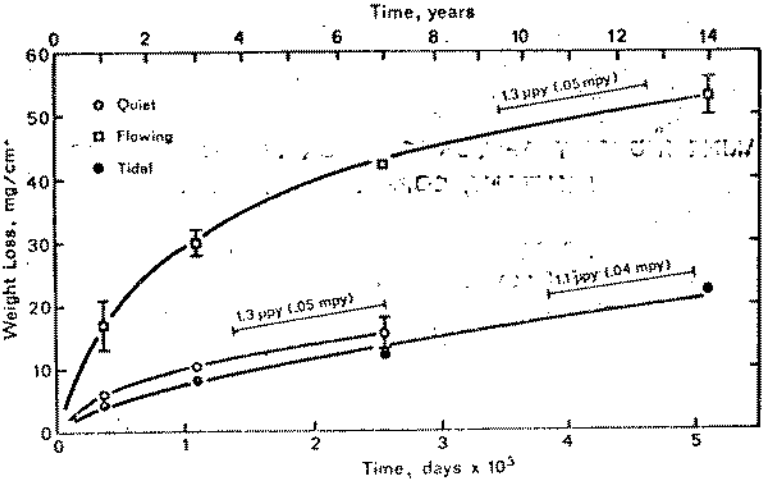

FIG. 1.—Chronogravimetric curves for 90/10 copper-nickel in quiet, flowing and tidal zone sea water [after EFIRD and ANDERSON (3)].

lishing itself as the preferred material for marine engineering use.

In many instances, the use of copper-nickel is associated with new engineering concepts which together offer major economic advantages for both ship-building and the emerging marine industries. This paper reviews some of the exciting, innovative developments whose viability stems from the unique combination of properties of 90/10 copper-nickel.

2. THE MARINE CORROSION AND BIOFOULING CHARACTERISTICS OF 90/10 COPPER-NICKEL

The corrosion and biofouling resistance of 90/10 copper-nickel in sea water is well documented (1-3). Even after several years exposure in sea water only very limited marine growth is likely to occur on a copper-nickel surface. These organisms are usually weakly attached and the surface may easily be brushed clean.

Under normal circumstances, the corrosion rate of copper-nickel in sea water is extremely low, although the rate is increased by the presence of pollutants (hydrogen sulphide and ammonia) and by high sea water velocities. The equilibrium corrosion rate for 90/10 copper-nickel in sea water flowing at 2 ft/sec was determined by EFIRD and ANDERSON (3) during 14 year exposure trials as 1.3 μm/year (Fig. 1), which for all practical purposes is negligible. In the same tests, only very light marine fouling attachment to the copper-nickel was observed over the 14 year period (Fig. 2).

Initially, the corrosion rate is higher, but it gradually stabilises to the low equilibrium level as a tightly adherent film of cuprous oxide forms on the surface. Over a period of time this film hydrolyses to cupric hydroxychloride $Cu(OH)_2 \cdot 3\ CuCl_2$. This overlayer is less adherent and may slough off at intervals.

The basis for the anti-fouling behaviour of the copper-nickel surface is believed to be due to the toxic nature of copper ions (4). Since copper is a natural constituent of sea water and one of the elements essential for life, it might be expected that marine organisms would show considerable tolerance to the metal, and in the case of the higher life forms this is undoubtedly true. However, simple micro-organisms such as bacteria, micro-algae and protozoa are highly sensitive to ionic copper (5). EFIRD in carefully documented studies, has shown that the rate of release of copper ions from a copper-nickel surface is too low for leaching of ions into the sea water to be the mechanism by which marine fouling is prevented. EFIRD concludes that the anti-fouling properties are due to the presence of free

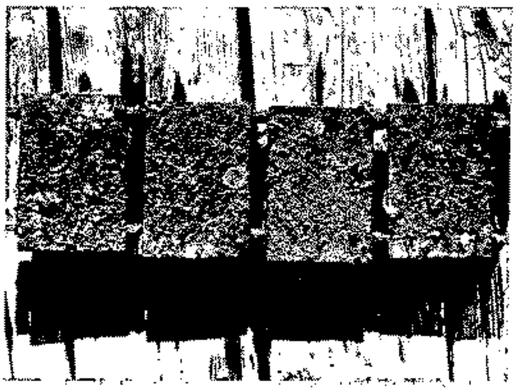

FIG. 2.—90/10 copper-nickel (left-2 panels) and 70/30 copper-nickel (right-2 panels) after 14 years' exposure in flowing sea water before cleaning. Very light fouling consisting of serpula, anomia and small barnacles has occurred [after EFIRD and ANDERSON (3)].

copper ions on the metal surface. There is also some circumstantial evidence to suggest that free nickel ions may also enhance the anti-fouling behaviour of copper ions (6).

Macro-fouling by barnacles, mussels, etc., of any type of surface does not occur until after colonies of micro-organisms have formed. This is believed to be a natural consequence of the micro-organisms' shorter life cycle and the fact that they spawn continuously in water, and not necessarily to a requirement by macro-organisms for the surface to be covered with bacterial slimes before settlement (7). The prevention and poor adhesion of macro-fouling on copper-nickel surfaces may not be related to the presence or absence of any initial micro-organism growth, but rather, as observed by WEISS (8), to the fact that the shells of organisms may be malformed. The nature of the organism's attachment cement (9) would suggest that it may have less strength if deposited as a relatively thick layer, as would be the case with a malformed shell. Possibly too, the attachment cement may be degraded by the catalytic effect of copper ions; this is a frequent problem with man-made adhesives. The weakly adhering cupric hydroxychloride film which forms on the copper-nickel surface is a further factor discouraging firm attachment of macro-organisms.

Copper-nickel is usually cathodic to other structural metals such as steel and aluminium and care should be taken to avoid electrical contact with a dissimilar metal which might produce a galvanic cell. Such galvanic cells have a double disadvantage in that they destroy the biofouling resistance of copper-nickel by preventing the surface release of copper ions, as well as encouraging more rapid corrosion of the anodic metal (10).

3. THE USE OF 90/10 COPPER-NICKEL IN THE MARINE AQUACULTURE INDUSTRY

Marine aquaculture, the commercial farming of fish and shellfish, is developing rapidly as the world's natural fish resources become depleted through over-trawling. Current world aquacultural production is approximately 6 million tons, some 10 % of the catch from open seas, but by the year 2000 it is anticipated that aquaculture will supply the majority of the world's fish requirement. Already in the USA, aquaculture is an $800 million retail industry concentrating mainly on luxury foods such as salmon, trout and shellfish.

Aquaculture farming methods are diverse. Some, particularly those in Asia, are centuries old, whilst others are the product of sophisticated, bio-engineering. The methods vary from ponds and enclosures to rafts, pens and cages anchored at sheltered points along the coast. Biofouling is a common problem in all these forms of farming. It is more severe in aquaculture than for any other marine industry, since in the selection of sites, the fish farmer naturally favour warm, high nutrient waters, ideal for biofouling growth.

In North America and Western Europe, the principal aquaculture interest is in raising salmon and these are usually grown in nylon bag net cages. The nylon netting biofouls readily and fouling can increase water drag loads on the cage structure five-fold in as little as two months (11). In addition, the strength of the synthetic netting is rapidly degraded by the marine environment and when near to the end of its useful like the bag net is prone to catastrophic failure from peak tides and storms. Similarly, the bag net is liable to damage by predators such as seals and birds, and these need only to make a small tear in the net for all the fish stock to be lost. The results

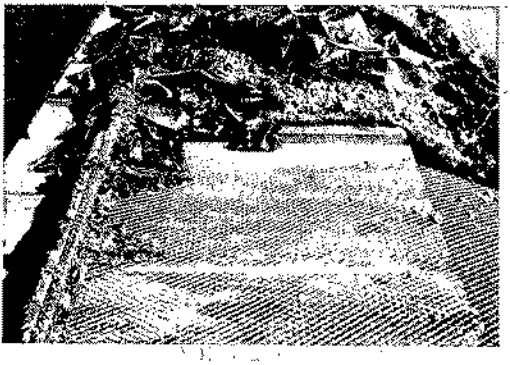

FIG. 3.—Copper-nickel mesh (foreground) showing less than 5 % blockage after 18 months in sea water compared with galvanised steel which is 95 % covered.

[illegible] at some farms have been so disastrous that fish stocks in nylon bag net cages are becoming virtually uninsurable.

In order to improve its life, netting is often treated with an anti-fouling solution, usually copper based. The anti-fouling treatment is generally effective for one to two years and the net must then be re-treated. The minimum copper ion leaching rate required to maintain fouling resistance is estimated at 10 to 20 micrograms/sq cm/day (12), that is at least, twenty times the normal release rate of copper ions from a copper-nickel surface. The initial copper release rate from anti-foulant coatings is much higher, but this appears to have no noticeable effect on the fish, probably because of the rapidity with which copper ions are diluted by the large volume of sea water passing through the cage, and in forming harmless complexes with organic and inorganic matter in the water (5).

Bouling of fish cages is one of the severest, high cost, maintenance problems encountered in large scale, commercial aquaculture. Fouling not only increases the weight and drag on the cage, it reduces water flow through the cage, thereby restricting the oxygen available to the fish. This, in turn, restricts the quantity of fish that may be safely stocked in the cage, and limits productions yields. The development of a fouling resistant copper-nickel mesh cage by INCRA is aimed at overcoming these problems, improving fish stocking densities and yields for a given size of cage, and in providing a cage which is more durable and more resistant to storm and predator damage (13).

Figure 3 dramatically illustrates the difference in biofouling resistance of various mesh materials after 18 months' submersion in sea water (13). 90/10 copper-nickel mesh showed the best biofouling resistance with only 5 % blocage. Aluminium bronze mesh and nylon netting treated with copper anti-foulant, were both 75 % blocked whilst untreated nylon netting was 85 % covered with heavy mussel sets. Worst of all was galvanised steel mesh which was 95 % blocked.

The INCRA cage shown in Figure 4 is based on the concept of using thin gauge, 90/10 copper-nickel in the form of expanded metal, 3/8 inch hexagon mesh of 76 % open area. The expanded metal is made up as modular panels, 1 m × 3 m with a glass reinforced plastic, channel frame. The modular panels are bolted together onto a GRP structural frame to produce a cage typically, 3 m × 3 m × 6 m, although because of the modular construction, cage sizes can be modified to suit specific site requirements.

The design of a prototype INCRA cage and the experience gained in its deployment at Fox Island Fisheries Inc, Maine, USA, has been described by HUGUENIN *et al.* (14). The cage, now in its third year of operation, has remained almost completely free of biofouling and has survived six of the most severe winter storms in Maine's history, without significant damage. As was expected, the external fibreglass structural framework and galvanised steel fittings were fouled, but the

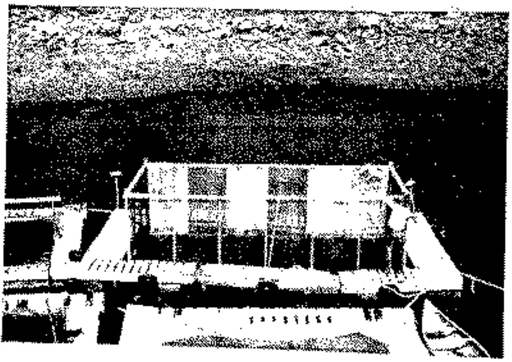

FIG. 4.—Prototype, INCRA floating fish cage sited at Fox Island Fisheries, Maine, USA.

mesh remained clear and there was no obstruction to water flow through the cage. In comparison, the conventional nylon bag net cages at the same site suffered severe storm damage, and because of heavy fouling, the nets had to be changed four times a year. The bag net cages were estimated to require a minimum of 40 man-hours per year per cage for net removal, cleaning, repair and replacement.

The use of 90/10 copper-nickel mesh for cages has attracted considerable attention in Europe. Its advantages in terms of sea water corrosion and biofouling resistance are now being exploited in the development of the INCRA modular panel system for new types of rotating and submersible cage. The submersible cage, in particular represents a major advance in commercial fish farming, offering low operational costs and freedom from storm damage, but its viability is due entirely to the biofouling and corrosion resistance of copper-nickel. INCRA, in co-operation with various Government agencies and commercial fish farms are now organising trials of copper-nickel mesh cages to evaluate a variety of cage designs, at sites along the Atlantic coast from Norway to Spain.

Copper-nickel mesh offers similar advantages in shellfish farming, where biofouling is no less of menace (10). Trials in Europe and the USA with copper-nickel mesh trays have demonstrated the advantages of lower maintenance costs through freedom from fouling, and longer service life as a consequence of the greater strength and resistance of the mesh to sea water damage. The commercial fish farmer, although initially hesitant to invest in the higher capital cost of copper-nickel mesh equipment, is now appreciating the major long term economies the use of this material offers in aquaculture operations and the added assurance it provides against complete stock losses from predator and storm damage.

4. FOULING RESISTANT, SEA WATER INTAKE LININGS AND SCREENS

Installations such as coastal power stations, chemical and desalination plants which use sea water as the cooling medium have a constant problem in preventing build up of marine fouling (15). Even larger volumes of sea water are likely to be required for Ocean Thermal Energy Conversion (OTEC) systems now being developed by many countries (16). It is necessary to provide screening of the sea water intake for these types of application in order to avoid damage to the pump equipment by debris. A further problem is that small organisms such as free swimming mussels and hard shelled larvae pass through the intake filters and grow on the intake system walls unless preventative measures are taken. Growth of mussels and barnacles on the walls reduces the intake diameter and sea water flow, which results in increased pumping costs. More importantly, they become dislodged and enter the more sophisticated section of the cooling system where they can block heat exchangers and cause crevice corrosion.

The most common system used to prevent growth of marine fouling is by chlorination. However, whilst this technique undoubtedly works provided that the chlorine injection systems are carefully monitored on a continuous basis, there is growing pressure from ecological and safety legislation which almost certainly necessitate consideration of alternative techniques. One of the most attractive is the use of copper-nickel solid or clad steel pipe or, more economically, sheating of concrete pipe with copper-nickel sheet (Fig. 5). Techniques for applying the sheet to new and existing concrete pipe are available using explosively driven pins (17).

The Office of Saline Water in the USA has carried out a cost study (18) which clearly shows that the use of copper-nickel for sea water intake linings is more economic than chlorination. The capital costs of installing both systems are comparable but the real benefit is derived from the negligible costs of operating a copper-nickel lining. In addition, copper-nickel, eliminates the dangers involved in transport and storage of large quantities of chlorine gas and has no adverse effect on the ecology in the vicinity of the point of its discharge into the sea. Copper-nickel intake linings have been installed in two power plants in the USA and are specified for large systems under construction in the Middle East and the USA.

Sea water intake screens are also rapidly

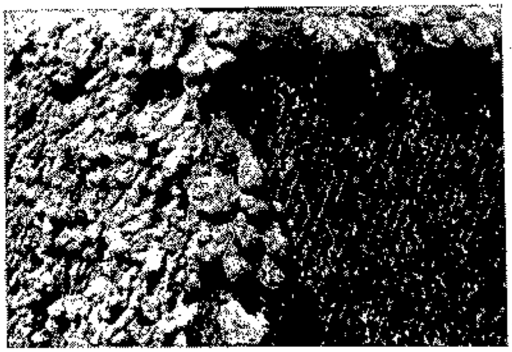

FIG. 5.—Expanded metal pump intake screen after one year service. Left side is carbon steel screen and right side is copper-nickel (insulated from steel).

fouled by marine organisms. A variety of methods have been adopted to keep screens clean, and in addition to chlorination, back flushing, high velocity water jets and mechanical brushing of screens have all been tried. None have proved totally satisfactory and most methods look even less attractive for proposed offshore OTEC plants where the size and inaccessability of the screens adds an extra dimension to the maintenance problem.

An alternative approach is to fabricate the intake screen from a material which is inherently biofouling resistant, such as the 90/10 copper-nickel mesh used for fish cages, as described earlier. The modular panel construction adopted for the INCRA fish cage makes it well suited for use in other marine screening systems (19). The individual panels are rugged and require little or no modification for sea water intake systems.

The use of 90/10 copper-nickel expanded metal for intake screens was first pioneered at INCO's Francis LaQue Corrosion Laboratory in North Carolina, USA. Copper-nickel 1.5 in × 1.5 in diamond mesh, with 260 openings/sq ft was used in these trials. The size of the intake screens was adjusted to suit the various pumping parameters, so that the sea water velocity through the screen averaged 0.1 ft/sec. Service performance of these screens in over nine years of use has been excellent (Figure 6). Similar successful performance is reported by the Alabama Department of Conservation and Natural Resources with 90/10 copper-nickel, 0.5 in. mesh screens.

Expanded copper-nickel mesh offers considerable design flexibility in that it can be produced in a large variety of mesh sizes, open areas and strand gauges to suit specific applications. A further advantage is that, unlike wire mesh, the nodes are fixed thus providing freedom from fretting and crevice corrosion. The excellent sea water corrosion resistance of the alloy makes it possible to design long-life, lightweight structures from relatively thin gauge expanded metal. Design data for predicting deflections and stresses on mesh panels subject to uniform loading is being determined in an on-going INCRA project at Groton Bio-Industries, USA (20).

Analysis and test data indicate that the INCRA modular mesh panel system can survive the dynamic loads resulting from a 3 knot (5.1 ft/sec) current even with complete trash blockage of the mesh. The deflection of the mesh under these conditions is substantial but still within the elastic range of the material. Fatigue flexure from tidal variation or any other source of cyclic loading, is likely to operate at such low stress levels that it should not present a problem.

The modular mesh panels when assembled with a suitable GRP space frame, provide a very strong and rigid structure. However, as with other screening systems, it is advisable to install a coarse bar rack upstream to exclude large drifting debris, as well as a means of removing the trash which accumulates over a period of time. The modular copper-nickel mesh structure is a promising new approach to meeting the requirement for a fouling

FIG. 6.—Copper-nickel lined concrete pipe after three years' immersion in sea water. Exterior concrete is heavily biofouled.

resistant screen, offering long service life and low maintenance.

5. COPPER-NICKEL SHEATHING OF OFFSHORE STRUCTURES

Prolific growth of marine plant and animal fouling on offshore structures in the North Sea has caused concern over the resultant increased loading on the structures. In addition, the free flow of sea water through the lattice structure is hindered, thereby increasing the stress levels and the susceptibility of the structure to fatigue damage. Fouling also hinders inspection and can lead to an enhanced rate of attack on the underlying metal. The problem of fouling is such that considerable effort (21) is being expended to ascertain the magnitude of the problem and methods for its alleviation.

The cost of removal of the fouling by divers or submersibles is substantial and it is, therefore, essential to minimise the level of fouling. Whilst anti-fouling paints offer an initial protection, they can only offer a limited life as the copper oxide pigment — the basis of their resistance to fouling — is leached out from the effective paint surface in a relatively short time. Since repainting of the structure is impracticable, a more permanent anti-fouling coating is required. Copper-nickel offers this long-term protection and, as it's corrosion rate in sea water is so low, only thin sections (0.1-0.25 mm) are required.

It is essential to insulate the copper-nickel from the steel structure and techniques for insulation and attachment to the horizontal and longitudinal cross members are having to be established and evaluated to determine their practical and economic viability. Two techniques are currently being examined both on site and in laboratory trials:

- *(a)* A duplex strip of 0.12 × 150 mm 90/10 copper-nickel backed with a 1.5 mm thick heavy duty nylon reinforced bitumen rubber compound. This backing acts as both a bonding to the steel structure and as an insulation from it. In laboratory trials, a wrapped pipe has been immersed at a potential of 1.20 V relative to a Ag/AgCl half cell using an impressed current cathodic protection system. After 10 months exposure, the current demand is less than 10 $\mu A/m^2$ and the resistance between the copper-nickel and steel pipe is greater than 200,000 ohms, indicating the effectiveness of the bitumastic as a water resistant insulating layer. On site evaluation trials are still in progress. This duplex coating is applied as a bandage and is suitable for underwater use by divers.
- *(b)* A duplex sheet of 0.25 mm thick copper-nickel adhesively bonded to a flexible rubber lining which can be wrapped around the steel pilings and cross members and held in place by a water proof zip fastener. On site evaluation trials on this protective antifouling system commence in March, 1980.

6. COPPER-NICKEL HULLED SHIPS

The cost of corrosion and fouling on conventional steel ships' hulls is substantial and in addition to this somewhat needless loss there is more importantly, an unnecessary waste of valuable energy resources, particularly, fuel oil. Marine fouling, and to a lesser extent, corrosion increase the surface roughness of the wetted surface of the hull, thereby increasing frictional drag. This results in an increase in fuel consumption of at least 10 % per annum, the extent depending upon the time since the last dry docking. This effect has been evaluated by many investigators (22-26) and typical values are those included in Table I.

Technically, the twin problems of marine fouling and corrosion on ships hulls can be overcome by the use of 90/10 copper-nickel.

FABRICATION

Copper-nickel has been a standard material of construction in the marine industry for many years. 90/10 copper-nickel will respond readily to most fabricating procedures (27) and is readily welded, usually with 70/30 copper-nickel filler wire or coated electrodes (28). It has been reported (29) that fabrication costs are only marginally greater than for steel and

TABLE I

LOSS IN PERFORMANCE DUE TO FOULING & CORROSION

Type of vessel	*Loss in performance (%)*	*Time out of dry dock*	*Source*
Naval frigate	45-70	3 years	Brown[1]
Container ship	35	18 months	Meek[2]
Container feeder ship	35	15 months	Milne[3]
Clyde steamer-Lucy Ashton	30	50 days	Smith[4]
VLCC	39	2 ½ years	Poole[5]

TABLE II

Vessel	*Length (m)*	*Launched*	*Built*	*Hull thickness (mm)*	*Operating*
Asperida II	16	1968	Holland	4	USA
Ilona	16	1968	Holland	4	Curacao
Copper Mariner	22	1971	Mexico	6	Nicaragua
Pink Lotus	17	1975	Mexico	4	Sri Lanka
Pink Jasmine	17	1975	Mexico	4	Sri Lanka
Pink Rose	17	1975	Mexico	4	Sri Lanka
Pink Orchid	17	1975	Mexico	4	Sri Lanka
Copper Mariner-II	25	1977	Mexico	6 + 2	Nicaragua
Sieglinde Marie	21	1978	UK	6	UK/Caribbean
Pretty Penny	10	1979	UK	3	UK

the better ductility of copper-nickel enabled contours of a complex curvature to be more readily achieved than on steel, e.g. the shape achieved in the area surrounding the propeller aperture and rudder horn on the Sieglinde Marie illustrated in Figure 7.

Consequently, few problems have been encountered in the fabrication of copper-nickel ships hulls, even by shipyards who were previously only experienced in fabricating steel hulls. Detailed information (29, 30), on the construction of two solid copper-nickel hulled vessels has been well documented.

In general, the plate thickness of the hulls on copper-nickel vessels has been similar to that of a conventional steel hull in spite of the fact that copper-nickel has a tensile strength about 2/3 that of steel. The reason for this is twofold, firstly, no corrosion allowance is necessary for copper-nickel and secondly, the strength of a ship hull is governed to a large extent by the framing which is the same construction for both steel or copper-nickel hulls. Some concern has been expressed over the relatively low yield strength of copper-nickels (10-12 tsi) when designing larger craft but this deficiency can be largely overcome by retention of about 6 % cold work from rolling

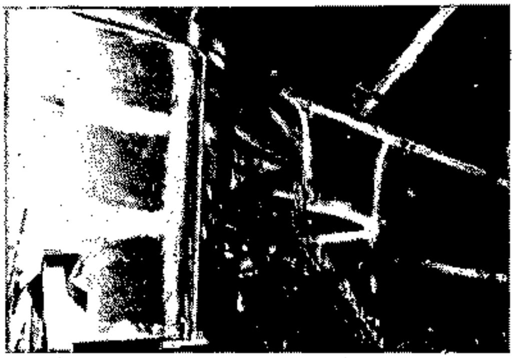

FIG. 7.—Area surrounding propeller aperture and rudder horn on "Sieglinde Marie" illustrating excellent fabricability of copper-nickel.

to achieve a yield strength of 18-22 tsi. This material is commercially available.

An alternative technique to achieve higher strength hulls is by the use of copper-nickel clad steel plate which is available from 2 manufacturers in Europe and 4 in total worldwide. In general this would be used in sections greater than 10 mm thick since, because of the production costs involved in cladding the two materials, it is more economic to use solid copper-nickel for the thinner sections. However, if strength is of prime importance and yield strength of the hull plate a critical factor in design then thinner sections than 10 mm could be justified.

The thickness of the clad copper-nickel on the steel base is normally between 2 and 3 mm thick; on calculation of corrosion rates and anticipated service life, this would appear to be excessive but mechanical strength, impact resistance and fabrication considerations, particularly alignment during welding, deem this thickness necessary.

In fact, a copper-nickel clad steel hulled vessel has already been constructed from an 8 mm thick plate comprising 6 mm of steel and 2 mm of copper-nickel. No fabrication problems of any consequence were encountered and constructional details and welding parameters are well documented (31).

SERVICE EXPERIENCE

10 vessels with copper-nickel hulls have been constructed in about as many years and as far as it is possible to ascertain, some vessels are operating in remote, often alien, areas of the world — all have operated without any operational problem or the recourse for hull cleaning or maintenance (Table II).

The corrosion rate measured on the copper-nickel hull of the Copper Mariner was only 0.05 mm in 4 years and the amount of fouling negligible, particularly when compared with its sister ship after 6 months in service which had been constructed in steel and painted with a conventional anti-corrosion, antifouling paint system (Fig. 8).

The thickness of the Asperida II hull plate was measured after 8 years in service and the maximum reduction in plate thickness was found to be 0.05 mm, ie. a corrosion rate of less than 0.01 mm/year. In 1979, the opportunity occurred to inspect the hull during a rare dry dock to refit the propeller shaft and repair some damage to the stern tube, the immaculate condition of the hull, free from fouling and roughening effects of corrosion can be seen in Figure 9.

ECONOMICS

After considerable experience, it is evident that there are no practical problems in construction or operation of copper-nickel hulls. The low corrosion rates observed, combined with absence of marine fouling, has fulfilled even the most optimistic expectations for this concept, and its greater use to date has been restricted only because of concern over the higher construction costs. The price of copper-nickel plate is about 10 times that of steel so that there is a considerable initial cost penalty in constructing a copper-nickel hull although the large difference in intrinsic metal prices is significantly reduced when considered as a function of the finished cost of a fabricated hull, and of even less significance in the context of the total cost of a sophisticated vessel.

The Copper Mariner was subjected to a close scrutiny of construction and operating costs when compared with a sister ship constructed from conventional materials and operating under similar working conditions. The economic analysis (30) showed that the pay-back period for the additional cost of the copper-nickel hull was 6.5 years.

FIG. 8.—The "Copper Mariner" (left) after 4 years' without drydocking compared with its sister ship "Jinotega" with a conventional, painted steel hull which was badly fouled after 6 months.

A more recent feasibility study (32) on the viability of a copper-nickel clad steel hull for a container ship showed a pay-back period of about 10 years using typical interest and inflation rates. However, with high inflation rates and an unnatural marketing situation in the shipping industry, which is subject to substantial subsidy, this pay-back period is probably overpessimistic in certain European countries. With the continuing rapid escalation in oil prices, the single highest cost factor in ships' operations, the copper-nickel concept can only become increasingly commercially attractive.

A recent cost comparability study (33) by Wavebreaker Marine (Scotland) Limited, a Scottish ship builder, has shown that for high speed vessels of 10-20 m in length the use of copper-nickel clad steel is highly competitive against glass reinforced plastic due to the rapidly escalating cost of GRP mouldings.

For example, on a 13.5 m conventional high speed launch, a GRP moulding would be £28,000 and for a copper-nickel cladded wetted area on a steel hull, £25,000. In this instance, where economic benefits exist both during construction and in service, the case for copper-nickel would appear to be irrefutable.

HIGH SPEED VESSELS

To date all copper-nickel vessels have been less than 25 m in length and have operated at speeds of less than 10 knots. Whilst the corrosion rates on the hulls of these vessels has been negligible, there was until recently some concern about the rates of attack which would be observed on vessels operating at high speeds. This aspect is particularly pertinent at present with the increased interest in copper-nickel for fast patrol boats, frigates and container ships which can operate up to 40 knots. However, a trial (34) carried out by Sun Ship in the USA has produced very encouraging results. A 24 knot container ship had test panels fitted to the hull and its rudder sheathed in copper-nickel sheet. After 14

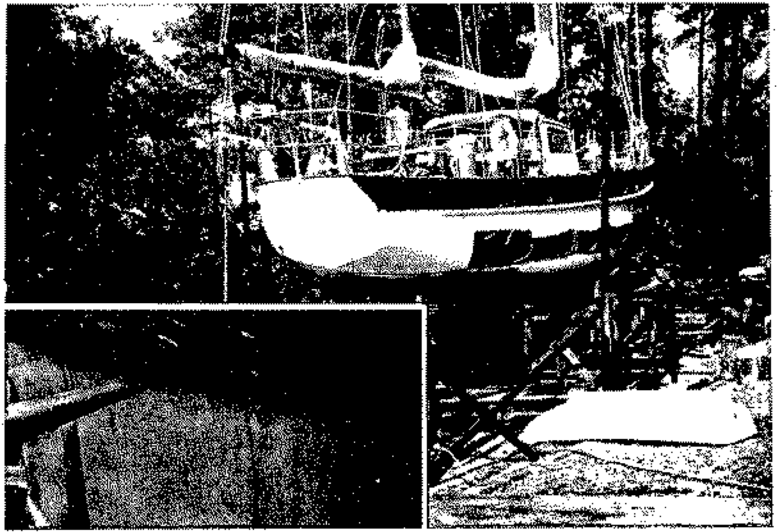

FIG. 9.—"Asperida II" after 12 years in service without any hull maintenance-note smooth surface free from fouling and corrosion.

months test on the 240 m vessel operating between Alaska and Washington, the maximum loss of metal was 0.08 mm with an average of 0.02 mm. These tests showed that if the copper-nickel could withstand the highly turbulent conditions existing in the vicinity of the propeller on a vessel operating at this speed, then it should be acceptable for hulls of high speed vessels. Confirmation of the effectiveness of copper-nickel for hulls and rudders of high speed vessels is currently being investigated by INCO using test panels attached to high speed vessels operating out of European ports.

In addition to the low corrosion rate observed in the Sun Ship tests, another remarkable observation was the polishing effect which had occurred in service. The copper-nickel on the rudder had a «mirror» finish and a surface roughness of only 20 μm, much smoother than the original surface of the plate, indicating a polishing effect in service. If this phenomena was reproduced on the hull of a high speed vessel then the ideal hull envisaged by TOWNSIN (35) would become a reality, i.e. a hydraulically smooth hull surface of less than 15 μm roughness which would be retained throughout the ship's life.

Construction, operating and now economic experience all indicate that copper-nickel hulled vessels can provide the answer to costly maintenance, conserve valuable fuel and allow naval patrol craft virtually 100 % availability.

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MACROFOULING IN THE CONDUITS OF A MIDDLE TYRRHENIAN POWER STATION

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INTRODUCTION

A good knowledge of the ecology of sessile marine organisms settled in the power station conduits is a need for increased efficiency in the control of marine fouling. In particular the knowledge of the settlement periods is necessary to the best way to control the fouling, i.e. to prevent larval settlement (Redfield and Hutchins, 1952; Straughan, 1972).

The power station of Torvaldaliga (one group of 200 MW and three of 320 MW) is situated along the Tyrrhenian coast 80 km North to Rome (Fig. 1). The water for the cooling system is pumped through 4 main conduits combined in two groups (20 m^3/sec and 30 m^3/sec) from sea to the power station. A part of the conduits is situated underwater and protected by two warfs. Before the water enters in the condenser, its velocity is slowed by an enlarged chamber and than flushed through a rotating screen. The water later is discharged into the sea. In the conduits the water velocity is between 0.5 and 1 m/s.

Six sites were choosen for immersion of panels in the following three main environmental conditions:

A) Intake channels, characterized by a high water velocity and general absence of light.

B) Basins at the end of the intakes, characterized by a lower water velocity than station A and the presence of light.

C) Discharge zones (outfalls) characterized by high water temperature (10° C higher than sea water entering the intakes), presence of light and high water turbulence.

So, in each station two sets of panels were considered together. The water intakes, conduits and chambers were examined when they were emptied for cleaning.

The aim of this investigation was to contribute towards a better understanding of the ecology of fouling organisms and in particular to knowledge of settlement periods in order to determine the best schedule for an antifouling system based on chlorination, though in this paper chlorination is not considered because it was used for a very short time. A second year investigation is in progress.

There are no previous work published on fouling of intakes in the middle Tyrrhenian power stations or factories. On the contrary it is available a lot of data dealing with organisms collected along the coast (Taramelli, 1969) and with fouling in Civitavecchia harbour (for a general review, see Taramelli and Chimenz, 1976).

MATERIALS AND METHODS

Settlement and recruitment of the fouling was studied between April 1978 and March

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1979 through the use of asbestos cement plates of 200 × 300 × 3 mm, immersed in six sites representing three main environmental conditions (stations A, B and C). Five panels stood vertically in each horizontal frame (Fig. 2); one panel was replaced every month, one every 3 months, the other ones after 6, 9 and 12 months. Asbestos cement was choosen because it provided a surface similar to the concrete walls of the conduits and chambers and because of the large use of this material in the fouling studies in Italian waters. At the recovery fouled panels were photographed and fixed in buffered formalin 10 % in sea water. The fouling was measured as wet weight (Figure 3), density of organisms (No./dm²), covered surface (coverage indices).

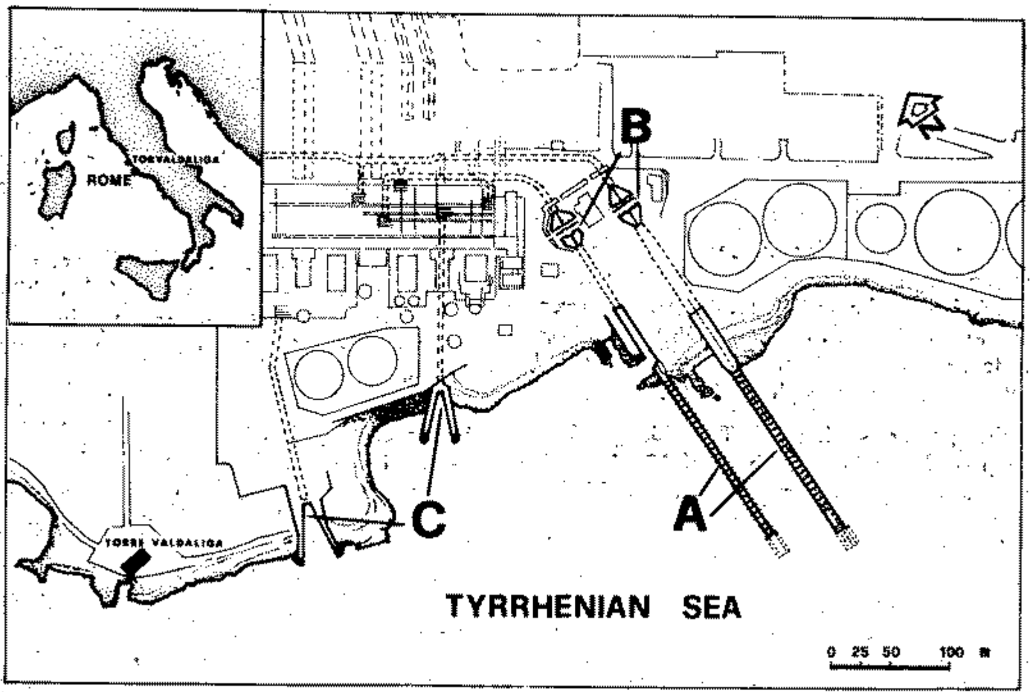

FIG. 1.—A simplified map of Torvaldaliga power station. A: Intakes conduits protected by warfs. B: Basins with rotating screen. C: Outfalls.

The water mains were inspected and fouling samples collected and photographed whenever the conduits were opened for servicing in November 3rd, 1977.

A comparison of the organisms on fouling plates and nearby walls of the chamber was made in June 5th 1979 and July 1979. Samples were weighted and examined in laboratory for description of organisms.

During this investigation the following parameters were measured; every day: temperature at B and C; every week: organic matter as chlorine demand at stations B and C; every 15 days: salinity at station B, nutrients ($N\text{-}NH_3$, $N\text{-}NO_2$, $N\text{-}NO_3$, $P\text{-}PO_4$) at station B, dissolved oxygen at stations A, B and C.

The temperature at station C was always about 10° C higher than at stations A and B. The high values of some nutrients were due probably to chemicals added to sea water and to the discharge of sewage. Data on dissolved oxygen were always higher than 6.9 ppm in all stations.

RESULTS

SPECIES RECORDED

Although more than 200 species of animals and algae were recorded on the panels, in general fouling was light especially on monthly panels. The main sessil animals are recorded in table I. To the list of table I to be added:

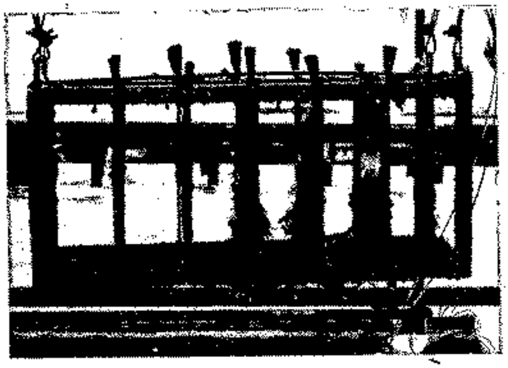

FIG. 2.—A frame containing 5 plates, replaced after 1, 3, 6, 9 and 12 months.

One species of actiniae; 4 of flat worms (plathelminthes); 3 of Nemertea; about 30 of non-serpulid polychaetes: *Eunice harassi* Audouin and Milne-Edwards, *Eulalia viridis* (Müller), *Platynereis dumerilii* (Audouin and Milne-Edwards), *Ceratonereis costae* Grube, *Syllis prolifera* Krohn, *Polyophthalmus pictus* (Dujardin), etc.; 4 of bivalves not listed in table I; 12 of not sessile gastropods: *Patella coerulea* L., *Rissoa guerini* Recluz, *Calliostoma laugieri* (Payradeau), *Gibbula racketti* Payradeau, *Ocinebra erinacea* (L.), *Hinia reticulata* (L.), etc.; 1 of chitons: *Acantochiton aeneus* Risso; 1 of mysidacea; 1 of tanaidacea: *Atanais robustus* Moore; 5 of isopods: *Dynamene bidentata* Adams, etc.; 21 of amphipods not constructing tubes: *Stenothoe valida* Dana, *Elasmopus rapax* A. Costa, *Caprella dilatata* Kroyer, *Caprella equilibra* Say, etc.; 6 of decapods: *Macropodia linaresi* Forest and Zariquiety, *Achaeus cranchii* Leach, *Pilumnus hirtelus* (L.), etc.; 4 of pycnogonids: *Anoplodactylus* sp., *Endeis spinosa* (Montagu), *Tanystylum conirostre* (Dohrn) and *Ammothella appendiculata* (Dohrn); 3 of echinoderms: *Ophiothrix fragilis* (Abildgaard), *Amphipholis squamata* (Delle Chiaje) and *Paracentrotus lividus* (Lamarck).

On panels were collected also algae (about 20 species) some belonging to genera *Ectocarpus*, *Dyctiota*, *Enteromorpha*, corallina, amphiroa and to encrusting red algae.

SETTLEMENT PERIOD

The settlement period of the main groups present on panels of the three stations are recorded in Figure 4 as percentage of covered surface by each group. Many groups settle quite all year long. The heaviest settlement of algae occured at station C, of animals at station B.

The settlements of main sessile fouling animals are reported in table II as density (No. of individuals/dm^2); the heaviest settlement of these species occurred during summer months with the exception of *Balanus perforatus* and *Mussels*. The latter species settled during spring, especially on panels exposed for period longer than one month: only small specimens have been collected on plates.

DOMINANT COMMUNITIES AND THEIR DEVELOPMENT

Different communities were observed in three stations (Fig. 5). At station A the main organisms on monthly substrates were the amphipod *Jassa falcata*, the barnacle *Balanus perforatus* and the hydroids *Tubularia crocea* and *Clytia hemisphaerica*. On panels immersed for longer period were important also serpulids, bivalves and bryozoans. The settlement was light after one-three month exposure, on six month plates hydroids and amphipods were dominant, after nine months of immersion the plate were covered mainly by bryozoans and amphipods; the latter group were dominant on 12 month panels together with cirripeds, molluscs and hydroids (Fig. 6).

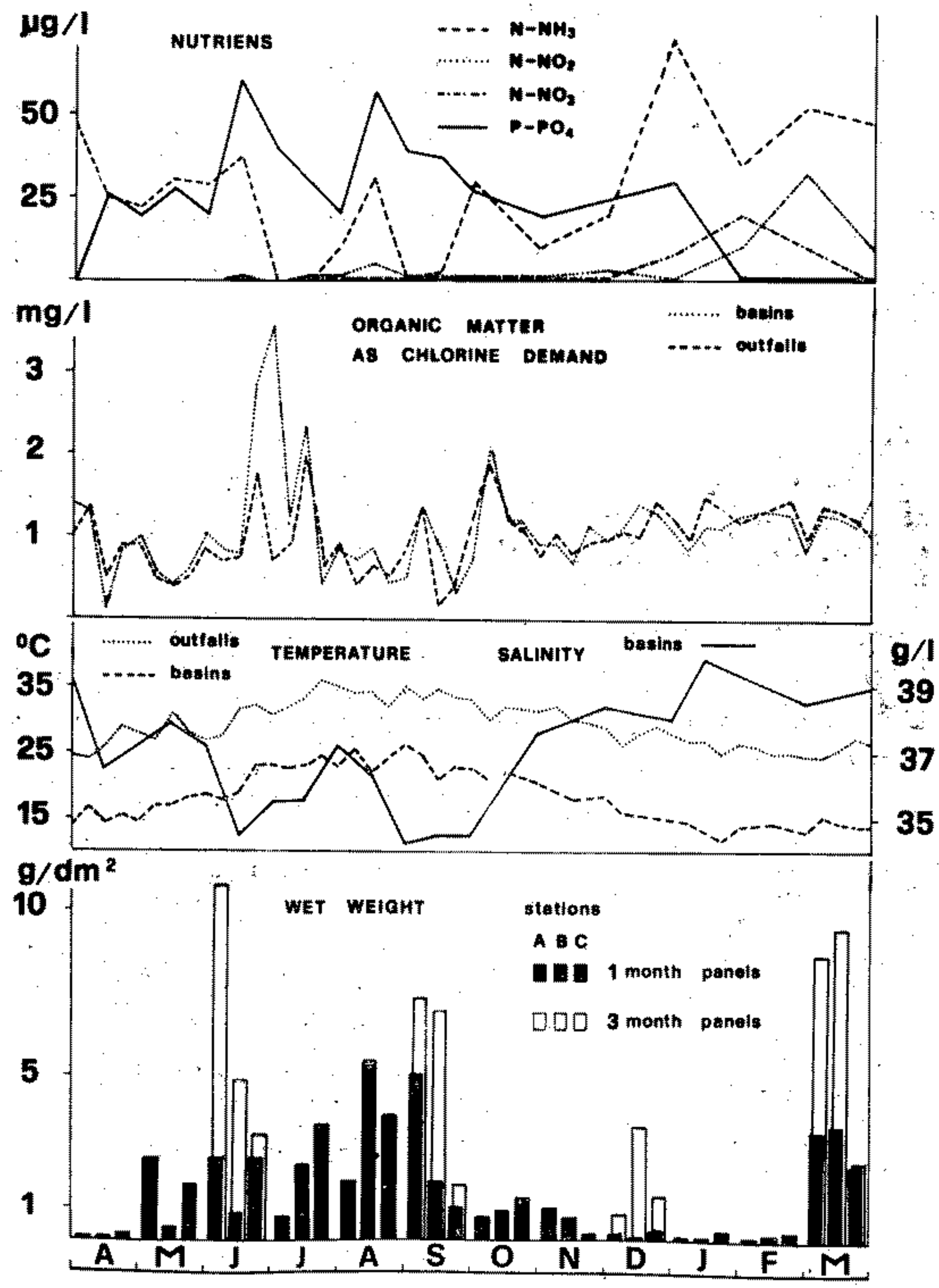

FIG. 3.—Wet weight values on monthly and three month panels exposed at three station A, B, C.

TABLE I.

LIST OF THE MAIN SESSIL ANIMALS FOUND ON PANELS

Sponges

Leucosolenia variabilis Haeckel.
Leuconia crambessa (Haeckel).
Leuconia solida (Schmidt).
Leuconia aspera (Schmidt).
Sycon ciliatum (Fabricius).
Clathrina coriacea (Montagu).

Hydroids

Tubularia crocea Agassiz.
Coryne pusilla Gaertner.
Eudendrium motzkossowskae Picard.
Clytia hemisphaerica (L.).
Campanularia integra MacGillivray.
Obelia geniculata (L.).
Obelia dichotoma (L.).
Laomedea calceolifera (Hincks).
Lafoeina tenuis G. O. Sars.
Aglaophenia tubiformis Markanner - Turneretscher.
Ventromma halecioides (Alder).
Plumularia setacea (L.).
Sertularella ellisi (Milne-Edwards).
Dynamena disticha (Bosc).

Serpulids

Serpula concharum Langerhans.
Hydroides dianthus (Verrill).
Hydroides pseudouncinata Zibrowius.
Hydroides nigra Zibrowius.
Hydroides helmata (Iroso).
Hydroides elegans (Haswell).
Vermiliopsis striaticeps (Grube).
Spirobranchus polytrema (Philippi).
Pomatoceros triqueter (L.).
Pomatoceros lamarckii (Quatrefages).
Josephella marenzelleri Caullery and Mesnil.
Filograna sp.
Pileolaria militaris Claparède.
Pileolaria pseudomilitaris (Thiriot - Quiévreux).
Janua pagenstecheri (Quatrefages).
Janua pseudocorrugata (Bush).

Gastropods

Bivonia triquetra (Bivona).

Bivalves

Mytilus galloprovincialis Lamarck.
Mytilaster minimus (Poli).
Musculus marmoratus (Forbes).
Ostrea edulis L.
Anomia ephippium L.
Hiatella sp.

Barnacles

Balanus perforatus Darwin.
Balanus amphitrite Darwin.
Balanus trigonus Bruguière.
Chthalamus stellatus (Poli).
Verruca stroemia (Muller).

Tube-builder amphipods

Corophium acutum Chèvreux.
Corophium insidiosum Crawford.
Corophium sexstonae Crawford.
Jassa falcata (Montagu).

Bryozoans

Aetea truncata (Landsborough).
Beania mirabilis (Johnston).
Bugula neritina (L.).
Caberea boryi (Audouin).
Scruparia ambigua (D'Orbigny).
Scrupocellaria bertholetti (Audouin).
Cryptosula pallasiana (Moll).
"*Cellepora*" *pumicosa* Auct.
Schizobrachiella sanguinea (Norman).
Schizoporella errata (Waters).
Schizoporella longirostris (Hincks).
Schizoporella sp.
Watersipora subovoidea (D'Orbigny).
Unidentified Ctenostomata.
Crisia denticulata (Lamarck).
Filicrisia geniculata (Milne - Edwards).

Ascidians

Diplosoma listerianum (Milne - Edwards).
Didemnum candidum Savigny.
Styela plicata (Lesueur).
Pyura squamulosa (Alder).

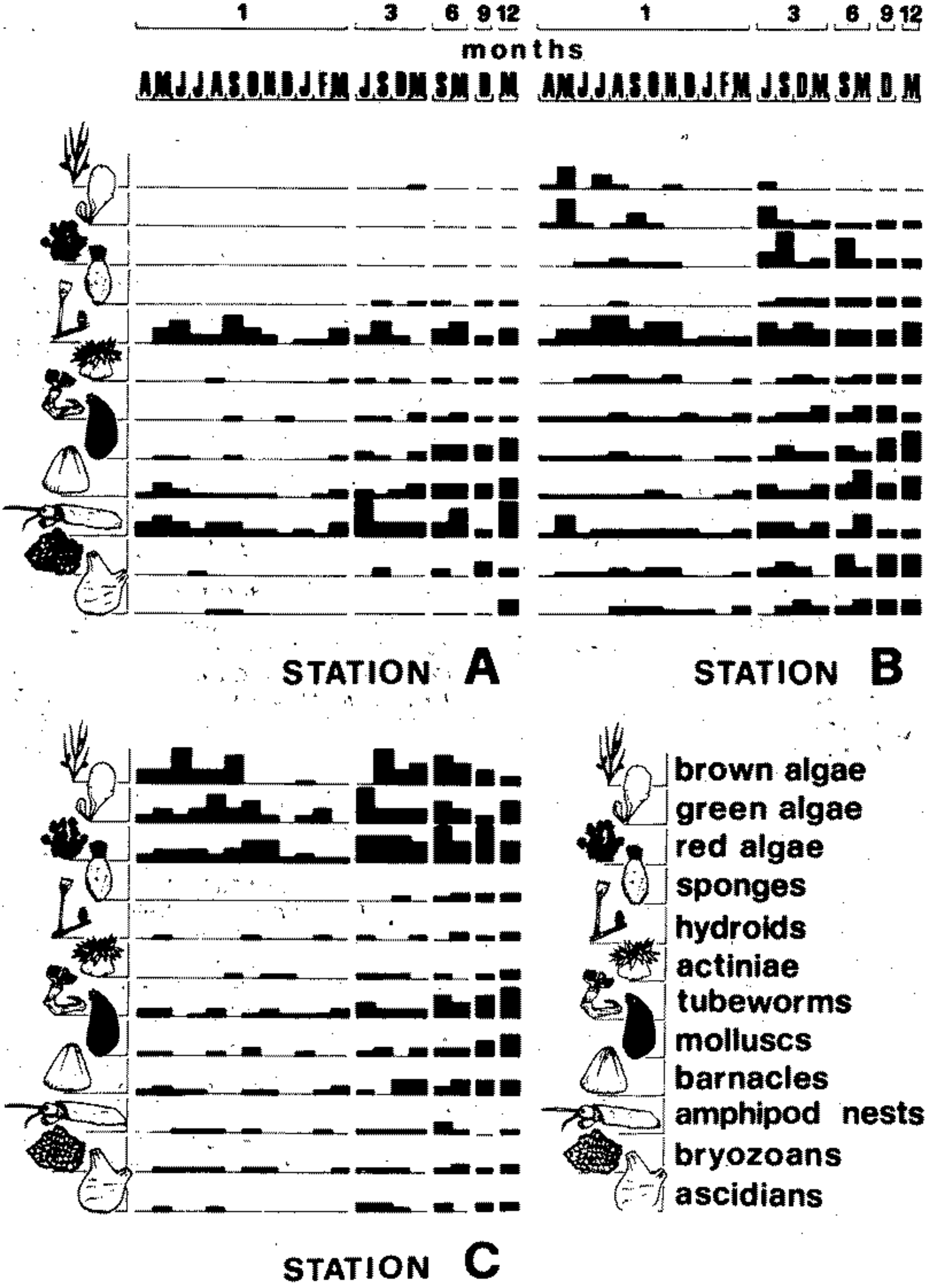

FIG. 4.—Variation of settlement on panels immersed for 1, 3, 6, 9 and 12 months at three stations. The height of each black column is proportional to percentage of surface covered by a group of organisms.

At station B the main organisms on monthly panels were amphipod, hydroids, serpulids, bivalves, barnacles, bryozoans and compound ascidians while on other panels also sponges, serpulids, actinians and algae (*Chlorophyta ulvales, Rodophyta corallinacee*) were important. During our investigation the community at this station had the following development: after one and three months algae were dominant, after six months bryozoans were the main organisms with molluscs, the latter group were dominant on nine month plates. On twelve month exposure plates the community was dominated by the bivalve *Anomia ephippium,* the hydroid *Sertularella ellisi,* the barnacle *Balanus perforatus* and the bryozoan *Scrupocellaria bertholetti* (Fig. 7).

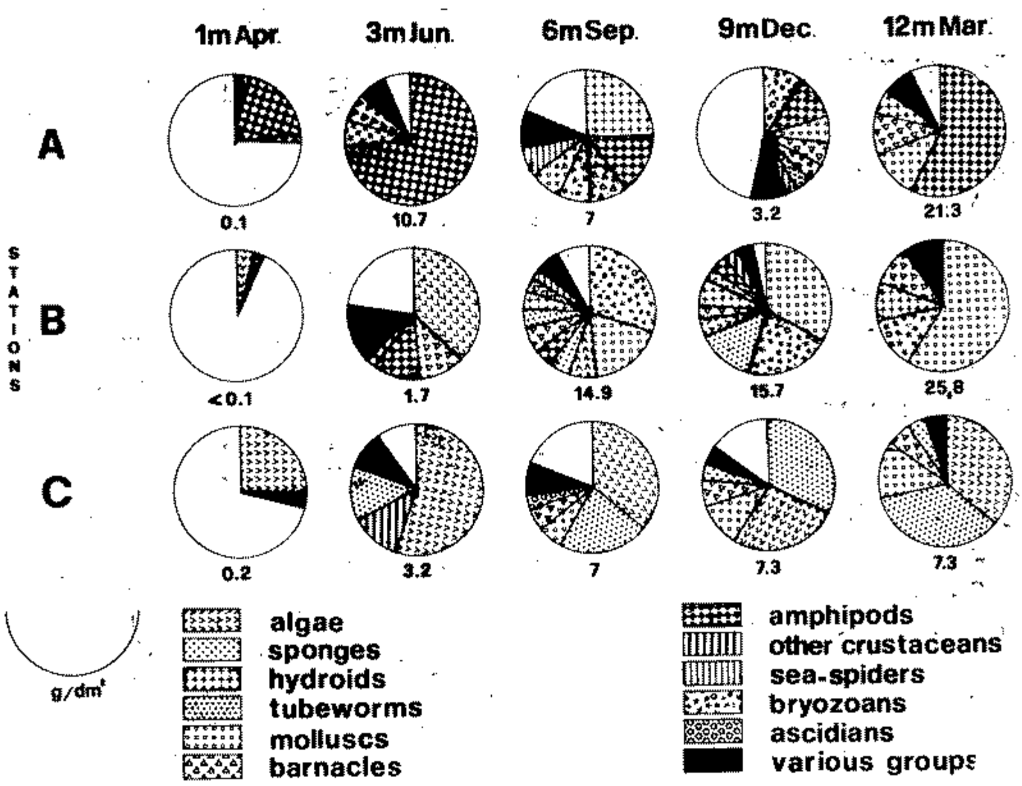

FIG. 5.—Development of communities with time of exposure at three stations. The number below the cicles represent wet weight (g/dm2). In a cicle each sector is proportional to the surface of panel occupyed by a fouling group.

At station C, algae (*Chlorophyta, phaeophyta* and *Rhodophyta*) were dominant both on monthly plates and on plates exposed for longer period. Only on the latter plates some animals were important, the spirorbid *Pileolaria pseudomilitaris,* hydroids, molluscs and barnacles. Also the development of the fouling community in this station was trongly influenced by algae. Only after nine and 12 month exposure the above mentioned animal groups were important. The final community was constitued by algae, spirorbid *P. pseudomilitaris,* mollusc vermetidae *Bivonia triquetra,* the barnacle *B. perforatus* and hydroids (Figure 8).

In general, the community at station B was assumed to be the most different and various in species composition.

Probably the fouling of station A was in-

TAB

SETTLEMENT OF MA

							I MONTH		
	April	*May*	*June*	*July*	*August*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
Tubularia crocea									
A		1	+	1	22	121	3		
B		7	5	10	302	20	46	3	
C		+							
Sertularella ellisi									
A		+							
B		+	4	+	+	3	6	4	+
C									
Pomatoc. lamarckii									
A									
B	+								
C	+						+		
Pileolaria pseudomil.									
A									
B		1	+	+	5	1	1	+	
C	13	25		1	104	2	4	1	
Janua pseudocorrug.									
A		+							
B	+	+	1	+	3	+			
C						+	+		
Bivonia triquetra									
A			+						
B		+	+	1	+				
C							+		
Mytilus galloprov.									
A		+				+			
B	+	+			+	+			
C									
Ostrea edulis									
A									
B				+	+				
C									
Anomia ephippium									
A						+			
B			+		2	+	+		
C					+		+		
Balanus perforatus									
A	+	1	+		+	+	+		
B	+	+		+		+	10	+	
C	+				+		1		

As No. ind./dm² (for hydroids, No. of stems/dm²); + = <1/dm².

E II

IN FOULING SPECIES

			3 MONTHS				6 MONTHS		9 M	12 M
January	*Feb.*	*March*	*June*	*Sept.*	*Dec.*	*March*	*Sept.*	*March*	*Dec.*	*March*
+	+	64		167	2	171	184	208	83	17
	2	3	18	49	23	118	111	2	6	2
	1									
		1					2	+	+	+
+	6	21	6	+	14	150	8	42	21	93
								+		
						+	+	5	+	1
	6	+	+		1		+	22	+	10
			+				+	2		3
				+					+	
		+	3	97	5		140	3	96	22
	+	15	1498	175	14		1262	462	312	422
				+			+			
		+	2	10	+		11	+	14	22
		+		+			+	126	+	3
							+		+	
			1	1	+		3		4	2
			2	+			2		2	1
		+	+			208	3	525	3	72
		1	1	+	+	104	2	42	1	3
								+		
				+			1		3	1
				4	+		3		4	3
				+			+		1	+
				1			2		3	2
				13	+	+	12	+	15	12
			+				1		1	+
		2	3		1	31	4	23	5	20
		1	1	1	2	30	3	1	2	9
		+	+		+	4	1	8	5	3

fluenced by the absence of light and velocity of the water while at station C high temperature and turbulence of the water were important element to affect the community.

ACCUMULATION

The amount of fouling was measured as wet weight, monthly and three months values are recorded in Figure 3.

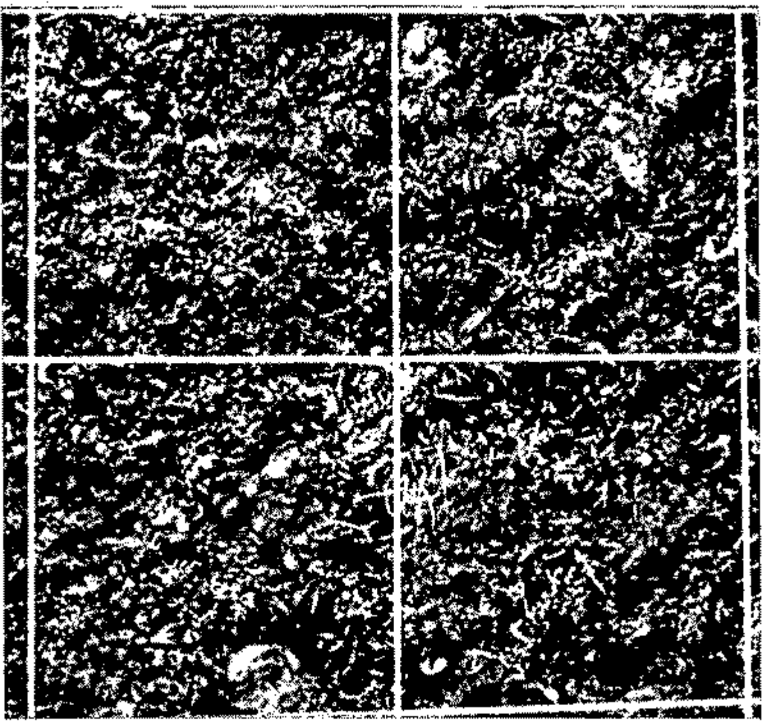

FIG. 6.—Fouling community at station A on a panel exposed during 12 months (each square is 5 × 5).

During this investigation the highest values were the following: 5 g/dm² for monthly plates (station A), 10.7 g/dm² for three months (at station A), 18.9 g/dm² after six months exposure (at station B), 15.7 g/dm² after nine months (station B) and 35.5 g/dm²/year (at station A).

In general these values are lighter than those observed in power stations of Liguria. The highest accumulation occurred during late summer and spring. Low values were recorded all years long at station C on all kind of plates: after one year the maximum wet weight was 7.3 g/dm².

FOULING ON WALLS

Samples of fouling were taken from concrete walls near the frames containing panels. At station A the community was dominated by mussels, amphipods tubes, hydroids, barnacles and serpulids were also present. The wet weight was from a minimum of 55.8 g/dm² to a maximum of 358 g/dm². At station B the community was constituted by amphipods, hydroids and small mussels accompanied by the mollusc *Anomia ephippium*. The wet weight was comprised from 17 g/dm² to

156 g/dm². At station C (discharge) the algae were the main components of the community with a maximum value of the wet weight of 350 g/dm².

CONCLUSIONS

The data obtained during the first year investigation allow some preliminary conclusions.

The fouling in the Torvaldaliga conduits is qualitatively very rich but quantitatively very poor (after one year exposure of panels); in fact more than 200 species have been recorded but the maximum wet weight was 35.5 g/dm² (on a twelve month panel). A very different pattern of fouling was described in previous work in the Ligurian power station conduits (Relini *et al.*, 1974, 1976; Relini, 1976) and also in Civitavecchia port (Taramelli and Chimenz, 1976). The main organisms recorded in three environmental conditions of Torvaldaliga were: station A: the hydroid *Tubularia crocea* Agassitz, the amphipod *Jassa falcata* (Montagu), the cirriped *Balanus perforatus* Darwin; station B: the bryozoans *Watersipora subovoidea* (D'Orbigny) and *Scrupocellaria bertholetti* (Audouin) and the bivalve *Anomia ephippium* L.; station C: numerous algae, particularly of the families Ulvaceae, Ectocarpaceae and Corallinaceae, and the spirorbid *Pileolaria pseudomilitaris* (Thiriot-Quiévreux).

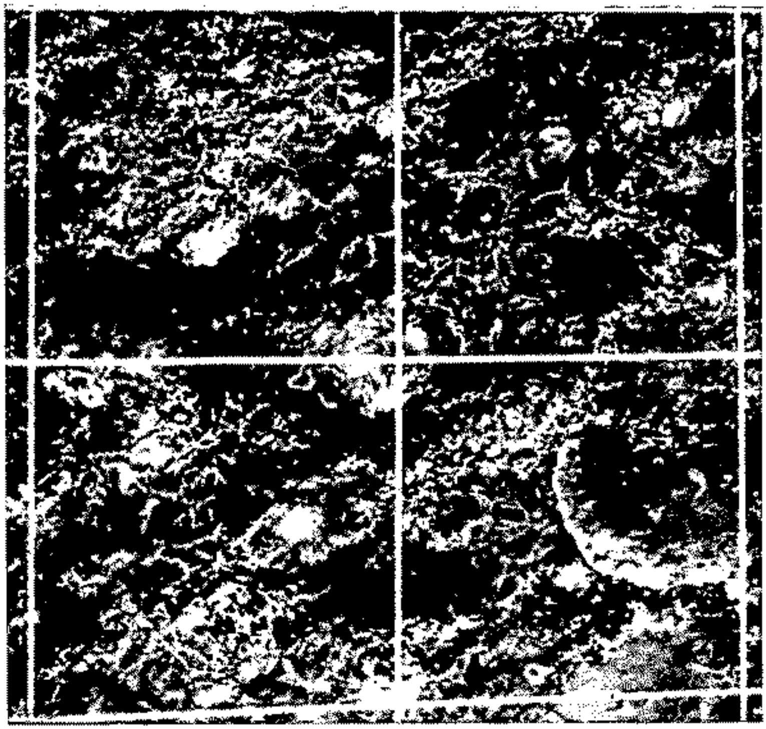

FIG. 7.—Fouling community at station B on a panel exposed during 12 months (each square is 5 × 5).

Settling of the principal fouling animal occurred in spring (*Balanus perforatus*, *Mytilus galloprovincialis*) and summer (*Tubularia crocrea*, spirorbid, ostrea, anomia, incrusting bryozians). The smallest diversity in community composition during the year occurred at station A where the greatest variations in weight and cover of the surface were recorded. The greatest diversity and seasonal variation occurred at station B. While at station C the cover was always high but the recorded weight were low. The fouling on plates was similar to that found on nearby walls with the exception of station A, because on the walls of this latter station mussels were dominant.

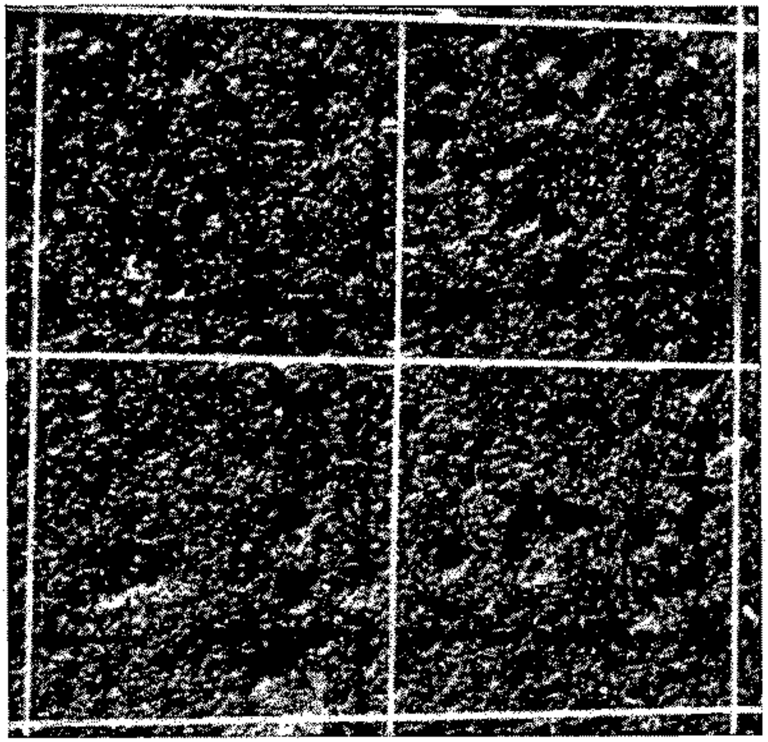

FIG. 8.—Fouling community at station C on a panel exposed during 12 months (each square is 5 × 5).

In fact on the panels settlement of mussels was sparse and they were not dominant at any of the stations. The abundance of large specimens of mussels inside the conduits was probably due to settlement during the previous year. Another explanation of the above mentioned difference can be found in the high settlement of *Mytilus galloprovincialis* in the last year during that plates have been immersed.

Usually after two years the fouling of the intake channels was dominated by mussels accompanied by amphipods, hydroids, barnacles and serpulids: the wet weight varied from 55 g/dm² to 358 g/dm².

The accumulation in the intake walls was much higher than fouling settled on panels after one year of immersion.

Finally the results of the first year investigation suggest that a successfull antifouling system would be operating from March to October to prevent settlement of macrofouling in the conduits.

SALISSURES BIOLOGIQUES DANS LES CONDUITES D'UNE CENTRALE THERMO-ELECTRIQUE DE LA MER TYRRHENIENNE MOYENNE

RESUME

Les salissures biologiques présentes dans les conduits de réfroidissement de la centrale thermo-électrique de Torvaldaliga (Civitavecchia, Italie) ont été examinées de l'avril 1978 au mars 1979, soit avec l'immersion de plaques expérimentales, soit avec l'examination directe des conduits au moment de leur nettoyage. Les plaques étaient immergées durant 1, 3, 6, 9 et 12 mois en trois stations le long du circuit hydraulique:

- Station A) Canaux d'aspiration: les eaux ont une vitesse très élevée et n'y a pas de lumière.
- Station B) Bassins: les eaux sont plus calmes et il y a de la lumière.
- Station C) Rejets: les eaux sont turbulentes, il y a de la lumière et la température est toujours plus haute (d'environ 10° C) qu'à l'extérieur.

Sur les plaques on a récolté plus de 200 espèces d'animaux et d'algues, mais en général la salissure était faible et le poids humide n'a jamais atteint des valeurs élevées (les maximums furent 5,4 g/dm² après un mois et 35,5 g/dm² après une année).

Les principaux organismes récoltés sont: à la station A, l'hydraire *Tubularia crocea* Agassiz, l'amphipode *Jassa falcata* (Montagu) et le cirrhipède *Balanus perforatus* Darwin; à la station B, les bryozoaires *Watersipora subovoidea* (D'Orbigny) et *Scrupocellaria bertholetti* (Audouin) et le bivalve *Anomia ephippium* L.; à la station C, nombreuses algues, surtout Ulvaceae, Ectocarpaceae et Corallinaceae, et le spirorbe *Pileolaria pseudomilitaris* (Thiriot-Quiévreux).

L'installation des moules sur les plaques fut très faible: ces organismes ne furent pas dominants dans aucune station. Ils l'étaient seulement dans les salissures des parois intérieures des canaux d'aspiration, où ils s'étaient probablement installés pendant l'année précedente; dans ces salissures, après deux ans, il y avait même des amphipodes, des hydraires, des balanes et des serpuliens: le poids humide variait de 55 g/dm² à 358 g/dm².

Au contraire de ce qui se passe normalement dans les mers italiennes, l'installation la plus massive ne s'est pas produite en été dans toutes les stations.

La station A a montré la plus petite diversité en espèces et les plus grandes variations du poids et de la couverture du substrat. On a observé la plus grande diversité et les plus remarquables variations saisonnières à la station B, tandis qu'à la station C il y avait toujours une couverture elevée mais un foids faible.

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PIEZOELECTRIC POLYMER HULL VIBRATORS FOR FOULING PREVENTION

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INTRODUCTION

Studies on the use of high frequency sound and vibration to reduce marine fouling have been carried out for at least 25 years. It appears that sound fields of very high intensity (10^6 Pa) kill the larvae of certain fouling species (1). Such high intensity sound has been used to prevent fouling on the glass windows of oceanographic sensors (2). However, high but sublethal sound levels (10^4 Pa) did not inhibit fouling (3). While the use of low intensity sound to repel selected marine species should not be excluded, sonic antifouling in general seems to require a high expenditure of energy.

Surface vibration appears to be effective in discouraging the adhesion of fouling species even at very low levels. For example, 16 ft aluminium boats vibrated at 22-55 kHz with 25 watt input (several watts/m^2) were relatively free of fouling (4). Furthermore, much lower vibration levels (.05 to .5 watt/m^2) applied to merchant ship hulls for periods of several years were sufficient to reduce fouling (5). It was noted that the vibration should not be interrupted because organisms would attach and could not be removed when vibration resumed. A number of ships in the Soviet fleet have been equiped with hull vibrators for over ten years. Antifouling has been effective on vibrating surfaces, but at welded areas of the bulkheads and framing where there was no vibration, heavy fouling resulted (6).

It is the objective of the present work to provide additional documentation relating surface vibration and fouling prevention, and to demonstrate a new and more efficient technique for producing surface vibration. Preliminary studies on the antifouling properties of test panels vibrated by piezoelectric plastic film have been reported (7). Further work with panels and boat hulls will be described in this report.

PIEZOELECTRIC FILM VIBRATORS

Conventional vibration transducers need to be fastened securely to the ribs or other supporting members on the inside of a boat hull. Most of their energy output is dissipated in

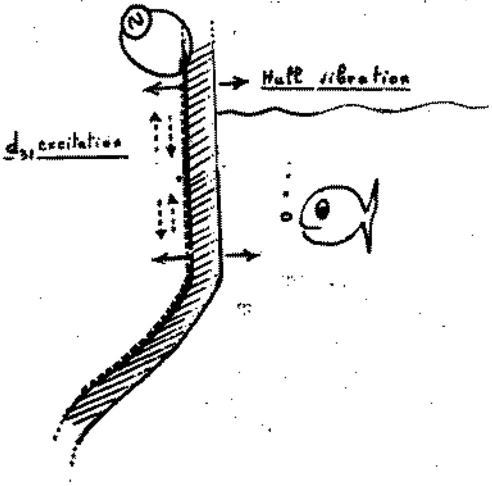

FIG. 1

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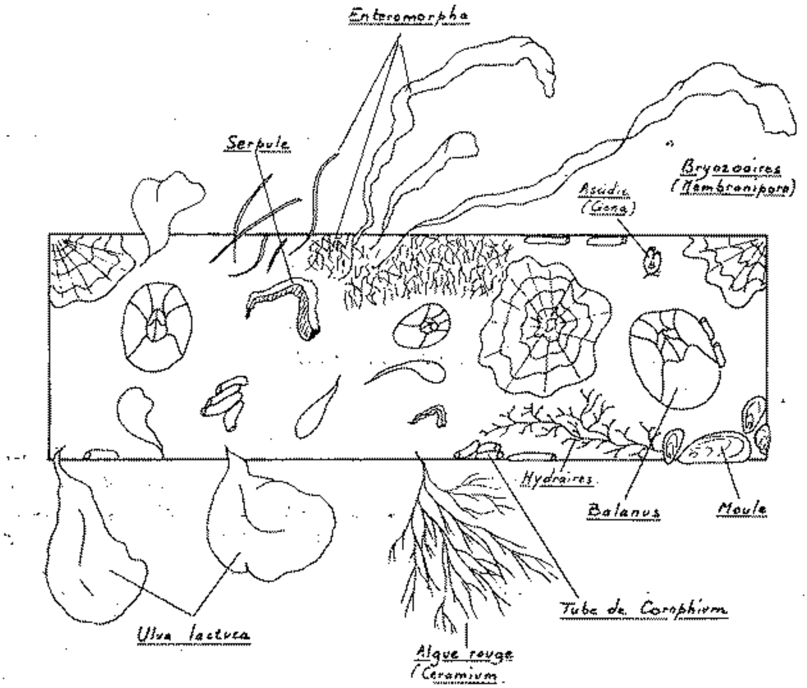

FIG. 2

these members resulting either in low vibration levels on the exterior surfaces, or high energy expenditures. A piezoelectric plastic film can be incorporated between the laminates of a fiberglass-polyester or wood hull near the surface. Such a structure would provide a much better dissipation of the energy of vibration at the surface where needed. Furthermore, a vibratile plastic skin could be provided for more massive structures.

Piezoelectric polyvinylidene fluoride was used as the vibration transducer in this work. (Kurea chemical of dimensions 1 to 10 cm wide × 20 cm long × .003 cm thick.) Films were metallized both sides, connected to a power supply, and bonded to the substrate using a marine epoxy. The power supply provided a 12 volt signal (5-24 V) at 5 or 24 kHz.

The piezoelectric strain coefficients of the film were approximately 18, 2 and 10 pC/Newton in the length, width and thickness expansion modes. Hence the film changed dimensions principally in length and thickness on excitation. These dimensional changes caused vibrations in the substrate normal to the surface as shown in Figure 1. Surface vibrations were measured as a function of frequency using a Bruel and Kjaer 4343 accelerometer and 2651 charge amplifier. Acoustic output was measured with a 8103 hydrophone. Vibration and acoustic spectra were obtained with a Tektronis 5L4N spectrum analyser and storage oscilloscope.

ANTIFOULING TESTS ON PANELS AND HULL MOCK-UPS

Antifouling studies have been carried out on several series of test panels 50 cm square × 2-5 mm thick. A piezofilm strip 1 × 20 cm was bonded to each panel. The strip and panel were covered with a polyester marine paint. Twenty microscope slides were attached to each panel for periodic removal and evaluation of adherent species. Panels were immersed in the Etang de Prévost, vibrated at 5 KHz

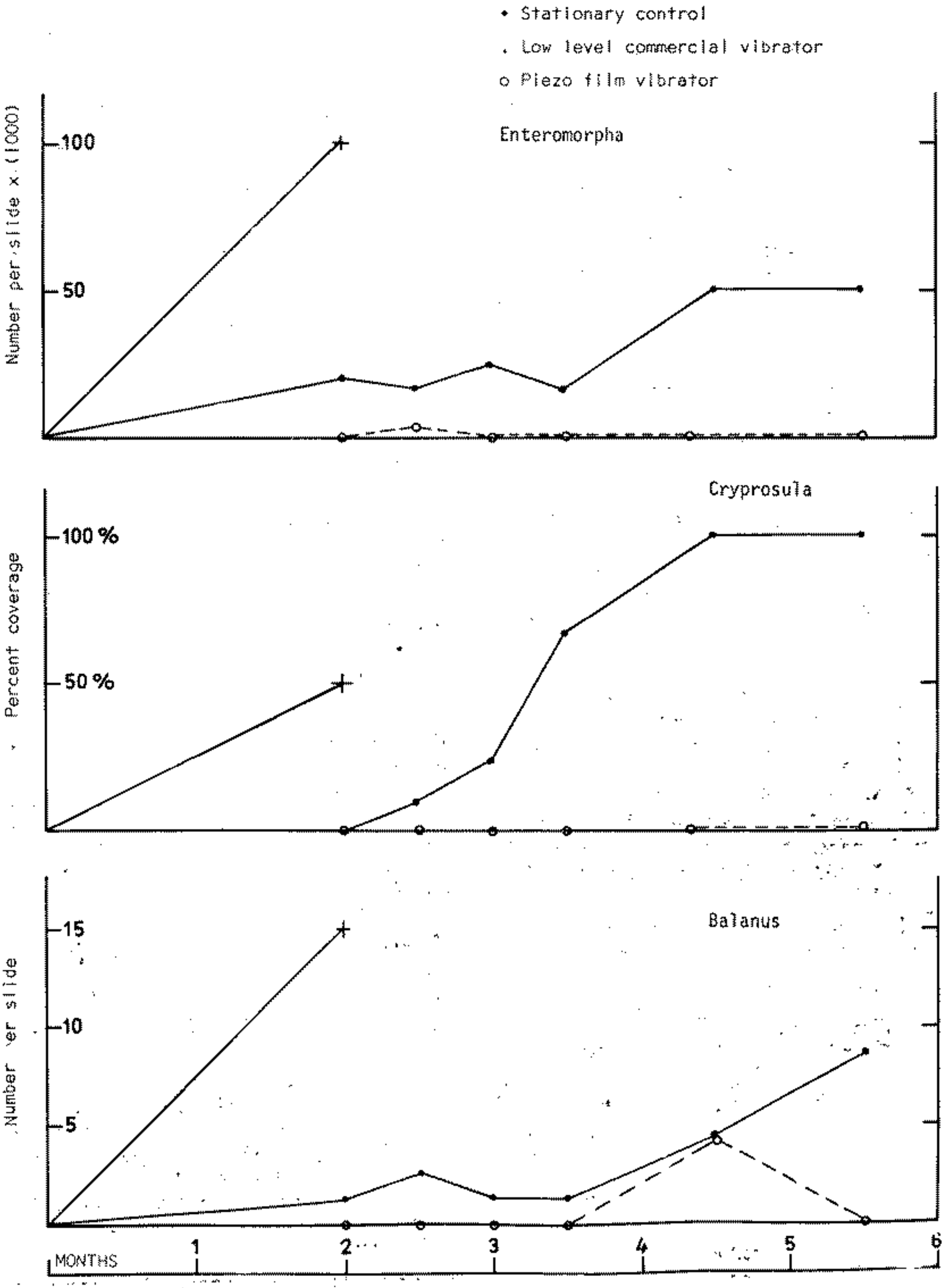
• Stationary control
. Low level commercial vibrator
o Piezo film vibrator
Enteromorpha
Number per slide x (1000)
100
50
Cryprosula
Percent coverage
100 %
50 %
Balanus
Number ver slide
15
10
5
MONTHS
1
2
3
4
5
6

Fig. 3

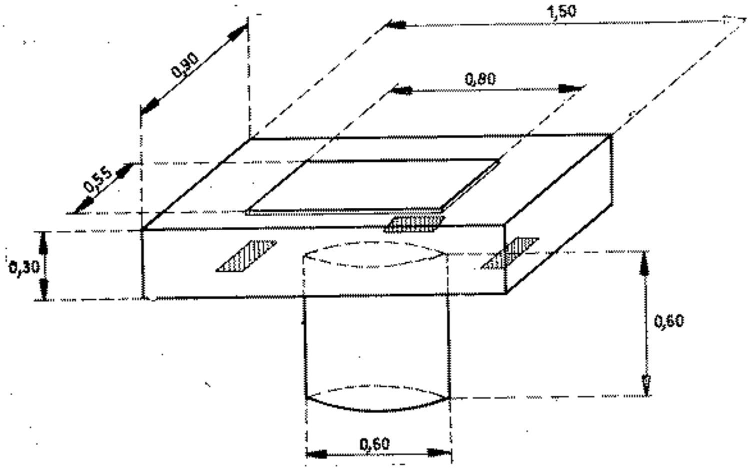

FIG. 4

and 0.01 to 0.1 G acceleration levels for periods of about six months.

Experiments were carried out in a region of the lagoon where it is connected by canal to the Mediterranean. The fouling species are well documented (8) and are characteristic of heavily polluted water (9). The principal fouling species were *Enteromorpha, Balanus, Mytilus, Serpula* and the briozoans *Membranipora membranaceae* and *Cryprosula pallasiana.* These species are shown in Figure 2 along with others which appeared less frequently. Microscope slides were removed from test and control panels every two weeks, stained with rose Bengal, and the adherent species documented.

The evolution of fouling on typical vibrating and control panels for the spring-summer period is shown in Figure 3. One panel was vibrated at about .05 G and 5 KHz by a piezofilm; a second was vibrated at about .005 G and 50 Hz by a commercial vibrator. The nonvibrating control panel was completely covered with fouling species in two months, the lightly vibrating panel in 5 months, while the piezofilm-excited panel was quite clean after 5.5 months. The three principal fouling species (algae, barnacles and briozoans) are shown in Figure 3, but the lesser species (worms, mussels, etc.) exhibited a similar aversion for the vibrating panels.

Three piezofilm strips were bonded to the inside of a 2 meter polyester-fiber glass skiff and vibrated at 5 KHz and 0.1 watt/m^2. The vibration output has high (.2 G) due to the

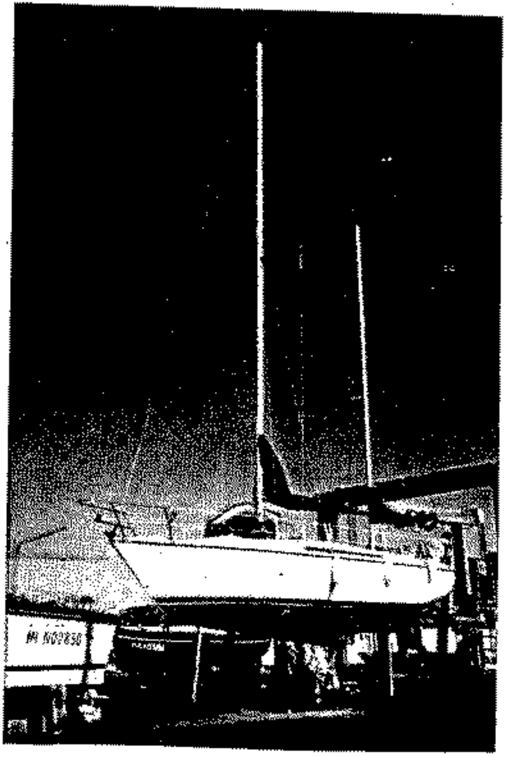

FIG. 5

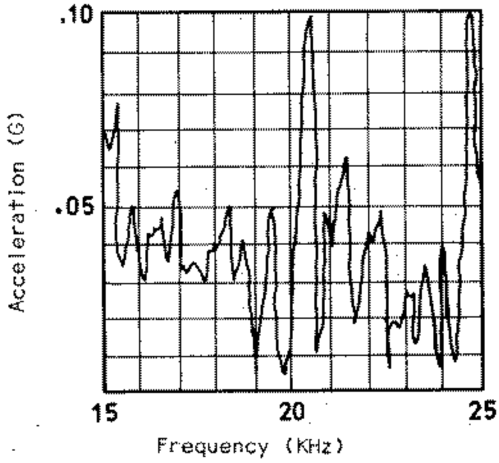

FIG. 6

thin hull. The skiff was moored in the Etang de Prévost for a 6 month period through the winter; no fouling was observed during the period.

While the results appear quite conclusive on a qualitative basis, insufficient work has been completed to provide quantitative relationships between vibration and fouling. It is anticipated that such quantitative date will be obtained from measurements in progress on test panels using different levels of vibration and varying duty cycles (periodically on and off). Hull simulators of aluminium (Fig. 4) and of fiber glass-polyester with piezofilms sandwitched betwen laminates also have been fabricated and are being evaluated. Antifouling studies are presently carried out in aquaculture basins supplied with seawater and protected from heavy weather.

CRUSING SAIL BOAT

An 11.5 meter crusing sail boat (Fig. 5) was fitted with 60 piezofilm strips, each 10 × × 20 cm in dimension. The strips were bonded to the inside of the hull near the water line at regions which were readily accessible. The hull consisted of a polyester-fiber glass laminate 1-2 cm thick. In practice, an installation of the films between laminate layers when forming the hull would improve surface vibration. When excited electrically, the films produced a vibration over most of the surface of the hull. Sweeping a frequency generator from 15 to 25 KHz produced vibration spectra of the sort shown in Figure 6. This is a typical spectrum showing many resonances which vary in frequency from point to point on the surface.

The films were excited during the test period by a generator operating at 24 KHz. The films presented essentially a capacitive load of 4.5 µF to the generator. Power consumption was 2 amp at 12 volt. A programmer limited the duty cycle to 25 % (0.5 min on, 1.5 min off) to reduce battery drain when power from

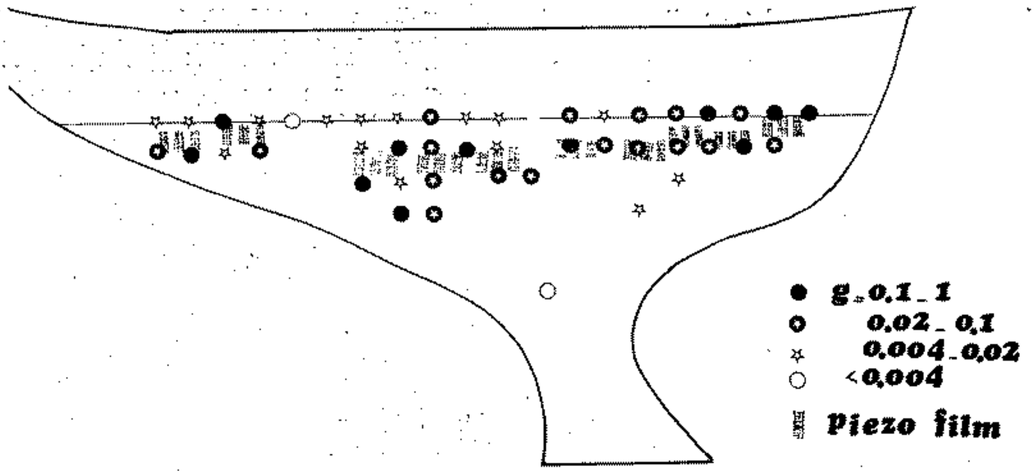

FIG. 7

shore or the motor generator was not available.

The vibration level produced by the 24 KHz generator varied along the hull from less than .004 G to 1 G (Fig. 7). The actual vibration level depended both on the proximity of the piezofilms and vibration damping near bulkheads, keel, etc. However, most of the hull surface near the water line was vibrated at a level of 0.01 to 1 G.

The hull was painted with conventional antifouling paint, except for a band of about 3 meter square near the water line. The ship was moored in *Sardinia* and *Corsica* and sailed throughout the Mediterranean from May until the end of December 1979. No fouling was observed on the hull during this period. The experiment was terminated in late December when the ship sustained severe damage in a gale.-

CONCLUSION

High frequency vibrations of low level discourage the attachment of most fouling species. Both vegetal and animal species are affected. Additional work is required to quantify minimum vibration levels and maximum periods of protection. Piezoelectric plastic films are effective vibration exciters especially for laminated ship hulls.

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ECOLOGICAL ASPECTS OF MARINE FOULING AT THE PORT OF MAR DEL PLATA (ARGENTINA)

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Argentina

ABSTRACT

This paper deals with the study of marine fouling communities developing on artificial inert panels placed on an experimental raft at the port of Mar del Plata, Argentina (38° 03' 17"S, 57° 31' 18" W). These results were obtained during the period 1973/74, although researches on local fouling communities have been carried out since 1965. Biomass fluctuations of fouling growth are analized. On short-term panels, these fluctuations are closely related to variations in water temperature. The settlement cycles of the main local fouling species are outlined and compared to those registered in previous assays. The ecological sequence of development of the fouling communities is also discussed. On the shallow panels, the community is dominated by the green algae *Enteromorpha* and *Ulva*, while the barnacles *Balanus amphitrite* and *B. trigonus*, the hydroids *Obelia angulosa* and *Gonothyraea inornata* and the polychaete *Polydora ligni* are common dominant forms on the deeper levels. In order to determinate the incidence of local barnacle settlement, a special assay was carried out with *Balanus amphitrite* and *B. trigonus*. These organisms cause serious damage on submerged structures and are highly resistant to toxics used in antifouling paints.

INTRODUCTION

Studies on marine fouling communities along Argentine coasts have been underway since 1965. A new assay carried out on experimental raft during the period 1973/74 has provided valuable information on the dynamics of local fouling communities.

Some new aspects which had not been previously considered were introduced in the research; biomass evaluations of communities developing on short and long-term panels were attempted in order to determine any possible correlation between biomass fluctuations and variations in environmental conditions. On the other hand, the use of experimental plates of minimum size has greatly facilitated the sampling task. Moreover, data on attachment seasons of species not considered in previous studies have contributed to a more accurate appreciation of local fouling communities.

Results of these researches are not only of considerable interest from an ecological point of view, but also constitute the basis for studies on the action of antifouling paints carried out simultaneously.

AREA OF STUDY

Studies were carried out in the port of Mar del Plata (38° 03' 17" S, 57° 31' 18" W) on account of its commercial importance and the highly intense fouling conditions which prevail in the area.

The topographical and hydrological charac-

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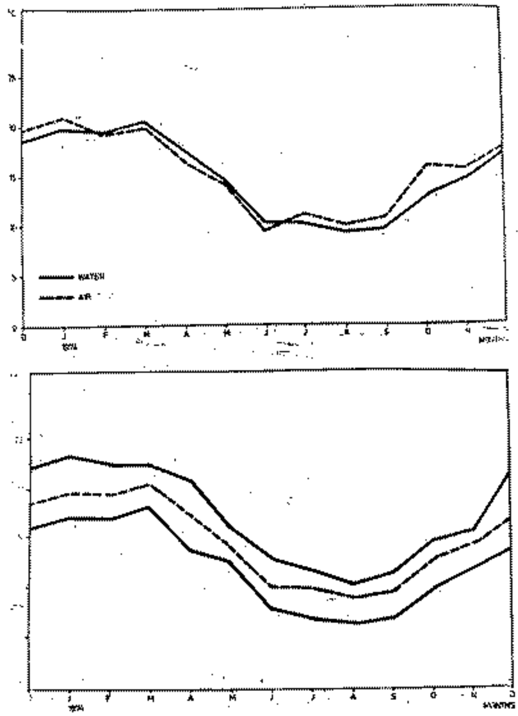


FIG. 1.—Mean water and air temperatures (up), maximum, mean and minimum water temperature (down) at the port of Mar del Plata, Argentina, December 1973/December 1974.

teristics of the port have been thoroughly described in previous papers (Bastida, 1971 *a* and *b*). Temperature records registered since 1965 show a great similarity in the general pattern of yearly variation. Absolute monthly temperature was found to be highest in January (23.2° C) and lowest in August (6.7° C), with an annual range of 16.5° C. The maximum mean monthly temperature was 21° C in March, while the minimum of 9° C occurred in August, with an annual range of mean temperatures of 12° C (fig. 1).

Figures for salinity were fairly constant, ranging from 32 to 33.7 % (fig. 2). Records for earlier years, however, show greater variations (31.4 to 35 % during 1966/67); in neighbouring areas salinity values are slightly higher, since the harbour zone is subject to the influence of sewage inflow, heavy rainfall and defficient water renewal.

Values for pH were consistently above pH = 7, except in September when an abnormally low value was recorded, probably associated with the inflow of polluted waters to the area during the low tide (figs. 1 and 2).

MATERIALS AND METHODS

As in previous studies (Bastida, 1971 *a* and *b*, 1972), an experimental raft was employed during the present research. The raft carried metallic frames, each holding four panels placed at different depths (fig. 3). Three of these panels, designated B, C and D, were attached at regular intervals between 0.5 and 2 m, while the top or waterline panel (A) remained only partially submerged.

Sandblasted inert acrylic panels 10 × 36 cm in the case of panels B, C and D, and 10 × × 46 cm for panel A, were chosen as experimental surfaces. Each test panel consisted

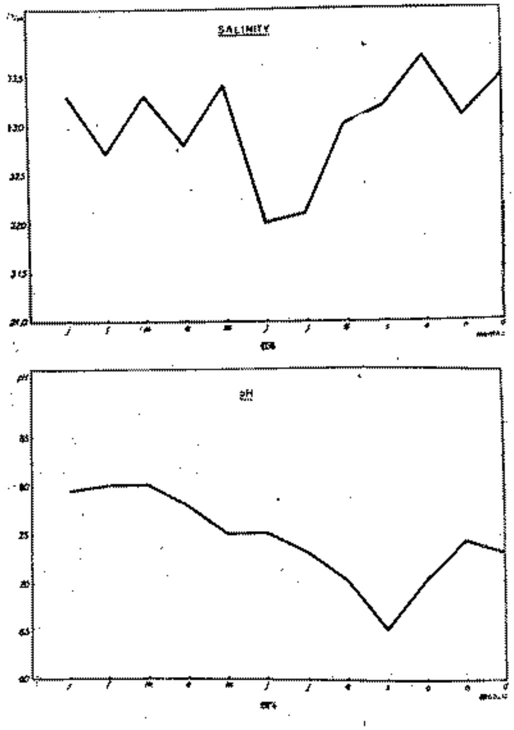


FIG. 2.—Salinity and pH at the port of Mar del Plata, Argentina, December 1973/December 1974.

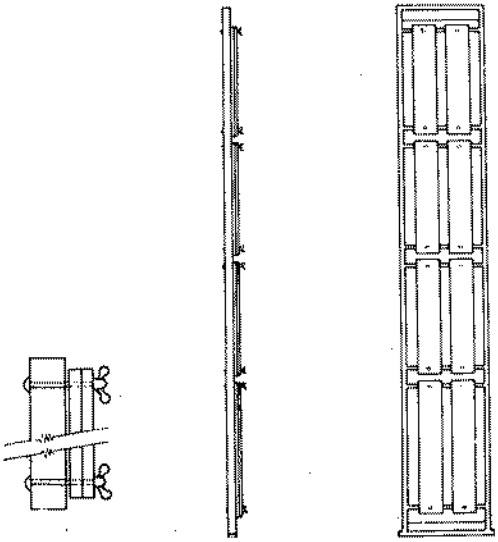


FIG. 3.—Raft frames containing test panels.

of two plates attached back to back with brass screws; one was used as a fouling sample and the other was separated for biomass analysis (figure 3). These panels were much smaller than those employed in previous assays and according to preliminar studies, provided a reasonably large area for fouling settlement and had the advantage of easy handling and examination in the laboratory (fig. 3).

The present study covered a period of one year, starting on December 18th, 1973, and ending on December 18th, 1974. One frame carrying a set of four panels (A, B, C and D) was removed every month; panels were withdrawn for examination and immediately replaced by clean ones. These constituted the short-term series and provided data on the seasons of settlement of fouling organisms. A second series of panels was exposed for progressively longer periods of time, starting from one month; one frame was withdrawn each month, leaving the remaining sets in place, so that the last frame removed at the end of the assay had been exposed for a full year. These panels were designated long-term panels, and provided information on the evolution of the fouling community.

Retrieved panels were photographed and placed in individual bags filled with a 5 % neutral solution of formalin in seawater. Once in the laboratory, panels were surveyed with a stereoscopic microscope and the distribution of the different species was sketched on a sheet of paper of equal area. Attached organisms were then scraped off and preserved for closer observation and identification.

Numerical abundance of the different species was estimated by means of relative abundance scale applied in previous studies (Bastida, 1968/75). This scale includes four categories: abundant (A); very common (VC); common (C), and rare (R). For biomass evaluations, the back plate of each panel was scraped clean and the scrapings were oven dried until weight was constant. Determinations of wet weight, ash weight and volume were also made and used as a complement of dry weight data.

RESULTS

BIOMASS FLUCTUATIONS

Fouling intensity on short-term panels in the port of Mar del Plata is directly related to water temperature. A correlation between developmental stages of the fouling community (Kawahara, 1962; Bastida, 1971 *b*) and water temperature has been consistently stated in previous studies (Bastida, 1971 *b;* Bastida and Adabbo, 1975). Consequently, a similar correlation was expected to exist between water temperature and biomass values registered during the present research.

Monthly mean water temperatures and fouling biomass of short-term panels (expressed as dry weight per surface unit) along the experimental period are shown graphically in

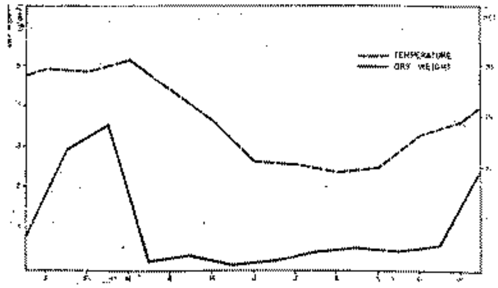


FIG. 4.—Mean water temperature and fouling biomass (dry weight) on short-term panels, taken as an average of panels A, B, C and D.

figure 4. Both curves exhibit a marked similarity suggesting that a correlation between fouling accumulation and prevailing water temperature does indeed exist. A biomass peak occured between February and March, with 3.48 g/dm² in dry weight. Then followed a sharp decline in biomass values and a minimum of 0.20 g/dm² was reached in the following month. Such a low value is in no way proportional to the slight temperature fall recorded during that same period and according to results of previous studies, the biomass minimum should have occured in September. The decrease should therefore be attributed to an environmental anomaly, probably pollution of the harbour waters, and since it was not registered on long-term panels, has probably affected reproduction and larval settlement. The biomass increase towards the end of the experimental period can be considered normal, for fouling growth increases very rapidly with rising temperatures (fig. 4).

On long-term panels, the effect of temperature on fouling weight was found to be only partial. Biomass and temperature curves show a marked resemblance only during the first months of exposure. This is due to the fact that temperature affects the initial process of colonization and the first stages of development of the community. During the later stages, biomass variations respond to dynamic processes of the community itself rather than to temperature fluctuations.

In this way, biomass increases steadily, coinciding with the progressive raise in temperature of the summer months, until a peak is reached between February and March. From March onwards temperature begins to decrease abruptly, while biomass values continue to increase, reaching the maximum value between June and July (37.42 g/dm²) (fig. 5).

As stated above, biomass fluctuations on long-term panels respond to internal mechanisms of the community, so that sharp declines are usually due to detachment of organisms having completed their life-cycles. During the present study, however, these fluctuations have been less important than in previous years, mainly because *Ciona intestinalis* has not dominated fouling assemblages, except in the community developed after a two-month period (fig. 15). This species, when dominant, accounts for more than 80 % of the total fouling biomass, itself constituting an important substrate for settlement of other organisms. Moreover, due to its rapid growth rate, specimens reach large sizes within short periods of time and become detached from the panels, carrying important amounts of fouling growth along with them.

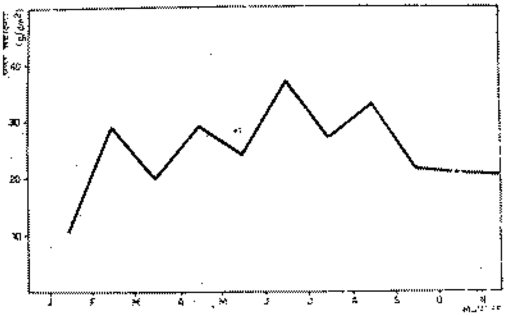


FIG. 5.—Fouling biomass (dry weight) on long-term panels, taken as an average of panels A, B, C and D.

In this way, the community suffers periodical declines, after which large areas of the panel become exposed and the process of colonization is reinitiated. During the present research, although the community has presented slight biomass fluctuations, no such drastic declines occured.

On the basis of the biomass data obtained during the period 1973/74, it was possible to evaluate the productivity at each of the four selected depth levels (A, B, C and D). Figures 6 and 7 show that those panels exhibiting the highest biomass values, both on the short and the long-term series, were the shallow panels (A and B). On the other hand, panels A and B also presented the highest species diversity, probably due to the presence of plant components which are absent of the deeper levels (figures 6 and 7).

PATTERNS OF SETTLEMENT ON SHORT-TERM PANELS

On the basis of the information obtained from panels submerged for monthly periods, it was possible to outline the seasons of settlement of the main local fouling species. Such information has been recorded continuously

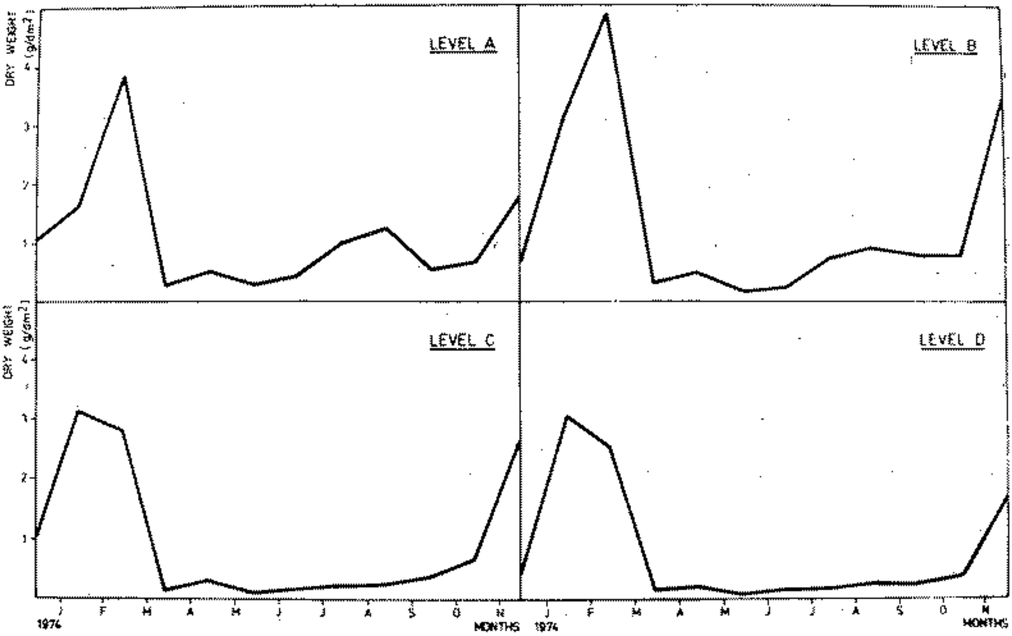


FIG. 6.—Fouling biomass (dry weight) on short-term panels at each of the four depth levels.

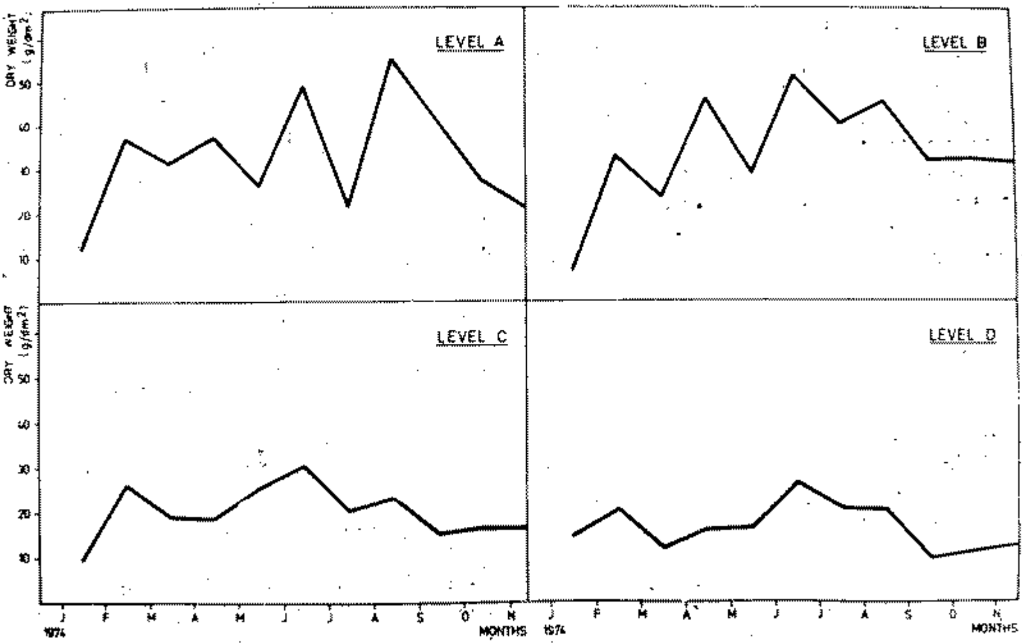


FIG. 7.—Fouling biomass (dry weight) on long-term panels at each of the four depth levels.

since the beginning of studies in the area. The major groups and organisms on short-term communities will be discussed briefly in the present chapter.

Diatoms

These organisms are particularly conspicuous during the first stages of fouling development, acting as pioneer settlers and constituting the basic food supply for other members of the community (Bastida and L'Hoste, 1976).

The group has been abundantly and consistently represented, both in species diversity as in number of individuals, reaching values of 10^4 individuals/cm^2 after approximately one week of exposure. Their abundance decreases with increasing depth and on dimly illuminated deeper levels where they must compete with better adapted organisms, they finally disappear.

Determinations at least to genus and when possible to species were made in all cases.

The main fouling diatoms found on test panels were *Navicula grevillei, Synedra* sp., *Licmophora abbreviata* and the planktonic form *Skeletonema costatum*. They have all appeared in high densities since the beginning of researches in the area.

The genus *Navicula* was represented by a number of species which are considered jointly in the graph (fig. 8), but the main settlement corresponded to *Navicula grevillei*. This species, one of the most prominent fouling diatoms in the area, forms filament-like masses which attain a length of several centimetres and are easily visible to the naked eye. Its presence has been detected throughout the whole year but most abundantly from mid-May onwards.

Synedra sp. has also presented an annual cycle, with peak density between mid-December and mid-July (fig. 8). In addition to its importance as an abundant settler on experimental plates, it is a fundamental diet component of numerous fouling organisms, such as *Siphonaria lessoni, Mytilus platensis, Sphaeroma* cf. *serratum, Corophium* cf. *insidiosum, Balanus amphitrite* and *B. trigonus*.

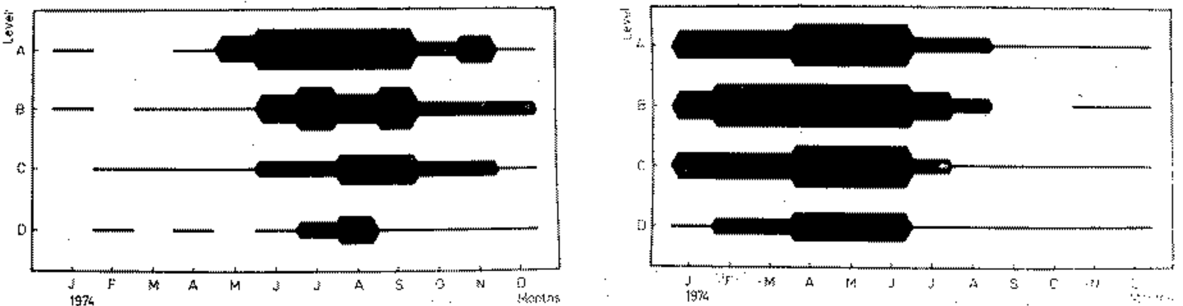
Another important fouling diatom was *Licmophora abbreviata* (fig. 8), which settled throughout the whole year but presented two periods of peak density (December to March and October until date of withdrawal). It is one of the main food items in the diet of several fouling organisms, namely *Halosydnella australis, Hydroides elegans, Siphonaria lessoni, Mytilus platensis, Idotea baltica, Sphaeroma* cf. *serratum, Corophium* cf. *insidiosum* and *Cyrtograpsus altimanus*, among others.

Skeletonema costatum (fig. 8) is one of the main planktonic species of the harbour area. Due to its abundance in the mass of water, this diatom is frequently registered on test panels. It was found to settle most intensively during the late spring and summer months and shows a marked preference for the deeper levels, probably as a result of deposition from the surrounding water. The importance of *Skeletonema costatum* is stressed by the fact that it forms part of the diet of filtering organisms such as *Merçierella enigmatica, Hydroides elegans, Balanus trigonus* and *Ciona intestinalis* (figure 8).

Pinnularia sp. (fig. 8), although less abundant than those mentioned above, has settled throughout the whole year and especially on the shallow panels.

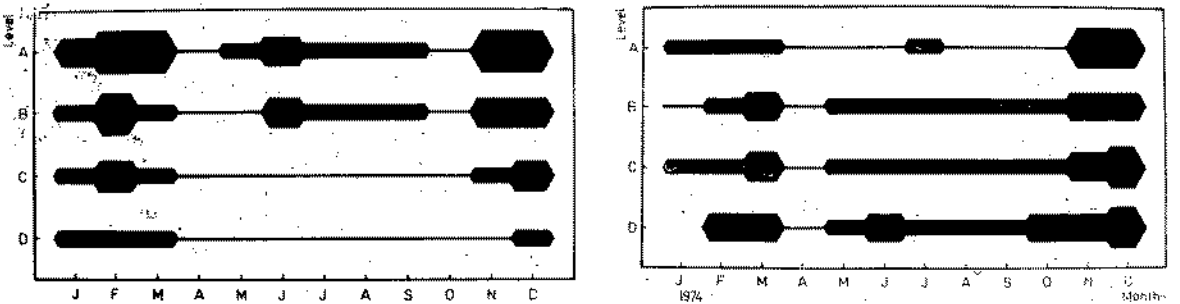
During the present study, some species were found in greater amounts as compared with previous records (Bastida and Adabbo, 1975). Such is the case of *Pleurosigma* sp. (fig. 8) and the planktonic forms *Nitzschia longissima* (figure 8) and *N. seriata* (fig. 8). This last diatom, though registered in very low densities, was comparatively more abundant than in previous years. *Nitzschia longissima* has presented a pattern of seasonal settlement, with a main period of colonization between August and November. During the summer months, it appeared only on the waterline panel, though in small numbers.

Other species, such as *Biddulphia aurita* var. *obtusa* and *Melosira sulcata* (fig. 9), have been important fouling diatoms in past years but were scantily represented during the present study. The remaining local diatom species were found in very low densities but their presence has been consistently registered on experimental plates since the beginning of studies in the area; in many cases, they are so poorly represented that it becomes impossible to outline their patterns of settlement. They were *Grammatophora* (mainly *G. marina*), *Asterionella japonica* (fig. 9), *Coscinodiscus* sp., *Tha-*



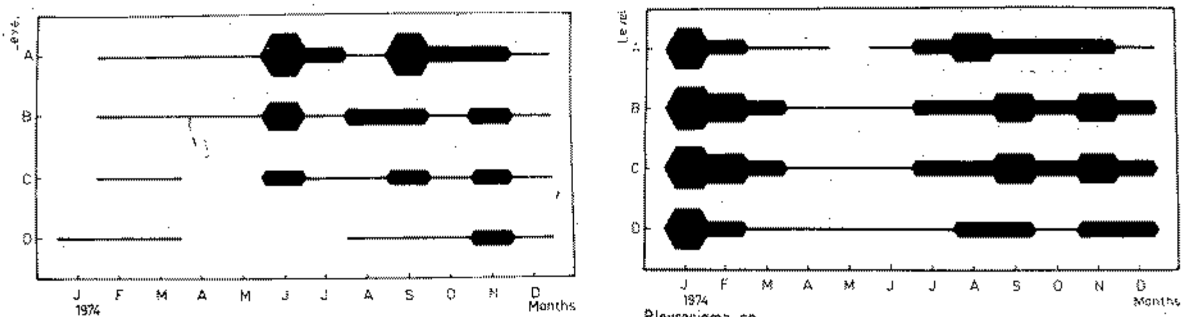
Navicula spp.

Synedra sp.



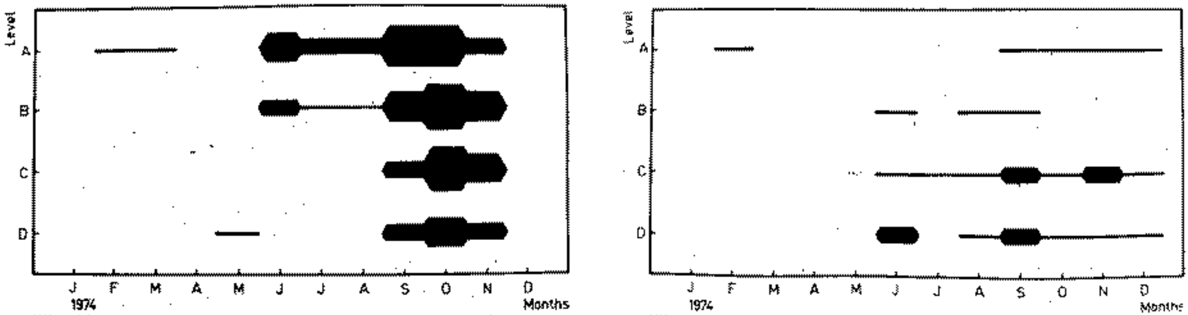
Licmophora abbreviata

Skeletonema costatum



Pinnularia sp.

Pleurosigma sp.



Nitzschia longissima

Nitzschia seriata

FIG. 8.—Settlement cycles on short-term panels.

lassionema nitzschioides, Stephanopyxis turris and *Thalassiosira decipiens.*

Green algae

They have been the dominant algae encountered on test panels, settling most abundantly on the waterline zone. They eventually become replaced by red algae, which dominate this level on longer immersed panels.

Enteromorpha intestinalis (fig. 9)

It is the most important chlorophyte of local fouling communities. Its main feature of settlement is its preference for the shallow panels, which is a direct consequence of favourable light conditions at this depth. In harbours of clear waters, *Enteromorpha intestinalis* has been found thriving at greater depths.

Although the settlement cycle can be considered an annual one, colonization is interrupted during the colder months and reinitiated at the beginning of spring. This settlement pattern has been repeatedly observed in previous assays (Bastida, 1971 *a* and *b*; Bastida and Adabbo, 1975).

Other species of *Enteromorpha* such as *E. prolifera* and *E. flexuosa* were also registered, though only rarely.

From a practical point of view, the various species of *Enteromorpha* rank among the most important fouling organisms, due to their strong resistance to toxics frequently employed in antifouling paints (Rascio and Bastida, 1973) and to their accelerated rate of growth (figure 9).

Protozoans

These organisms are the most prominent animal settlers on newly immersed panels. Mainly represented by ciliates, they are found throughout the whole year and at all depths. They settle shortly after colonization by bacteria and diatoms, feeding on these organisms as well as on organic detritus usually associated with bacteria.

Protozoans take part in the process of disintegration of dead material and constitute a food source for larvae of barnacles, bivalves, copepods and serpulids, as well as for many adult forms of filtering species. They are more abundant in harbour waters than in neighbouring areas, principally as a result of organic water pollution. Some of them, like the stalked ciliate *Zoothamnium* sp., are good indicators of polluted waters.

Zoothamnium sp. (fig. 9)

This was the most abundant protozoan encountered on test surfaces, both in the present study as in previous assays. It settles throughout the whole year and especially on the deeper panels. A period of minimum settlement extending from February to March and coinciding with the heavier summer fouling is probably a result of exclusion by other organisms.

The related species *Vorticella* sp. (fig. 9) was also frequently encountered on test panels, particularly during the course of this study. It was recorded throughout the whole year except in December, April and August, though less abundantly than *Zoothamnium* and, like the latter, on the deeper panels.

Condylostoma sp. has been observed in low densities during most part of the year. In the port of Mar del Plata, this protozan has appeared on test panels only in recent years. Three species of suctorians, *Acineta* sp. (fig. 9), *Ephelota* sp. and *Podophrya* sp. have settled seasonally and in low numbers. The tintinnids *Tintinnopsis* spp., *Favella* sp. and *Tintinnus* sp. were encountered only rarely.

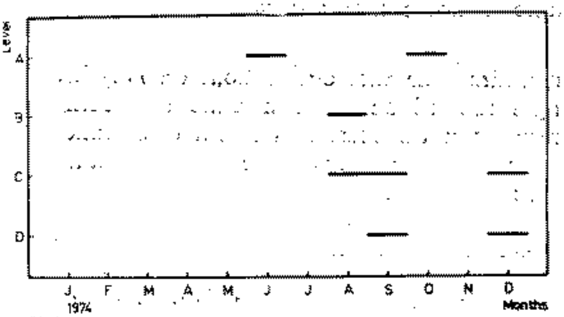
Hydroids

The most conspicuous features of these organisms are their high growth rate and their ability to settle at all depths. The absence of sea anemones from test panels is noteworthy, for they are found growing in great numbers on nearby submerged structures and all along the rocky shore of the Mar del Plata area.

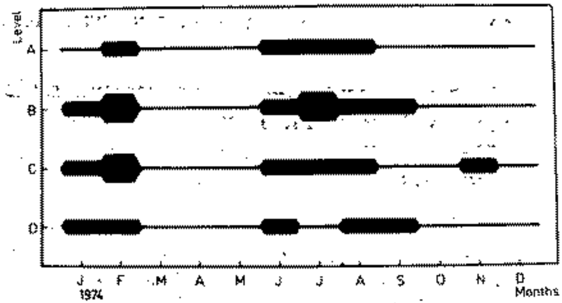
Gonothyraea inornata and *Obelia angulosa* (fig. 9)

These two species settle simultaneously and exhibit similar cycles, although the first is consistently more abundant than the latter. By virtue of their extremely rapid growth rate, they frequently attain sexual maturity and reach the end of their life-cycle within a single month.

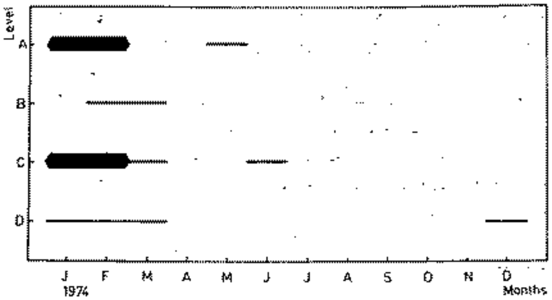
During the period 1973/74, these two spe-



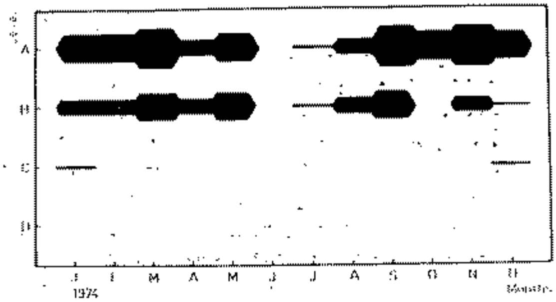
Biddulphia aurita



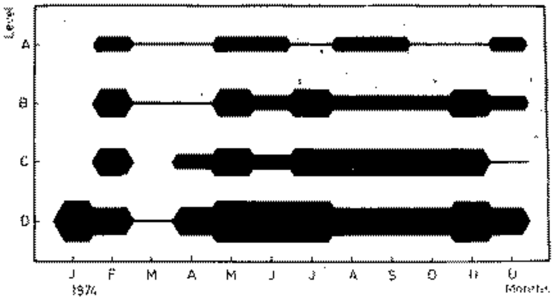
Melosira sulcata



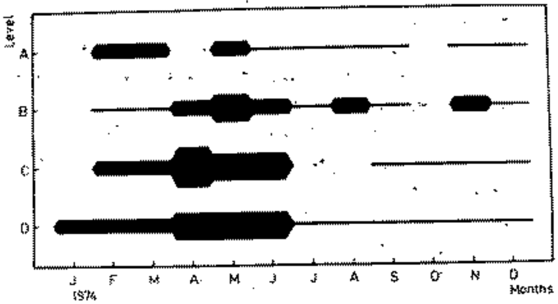
Asterionella japonica



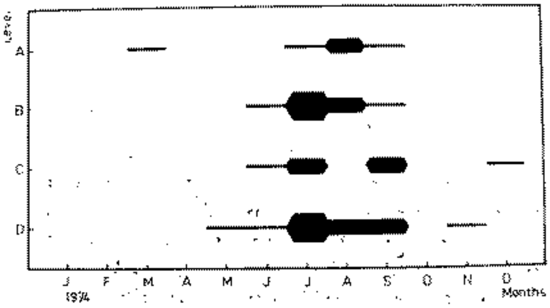
Enteromorpha intestinalis



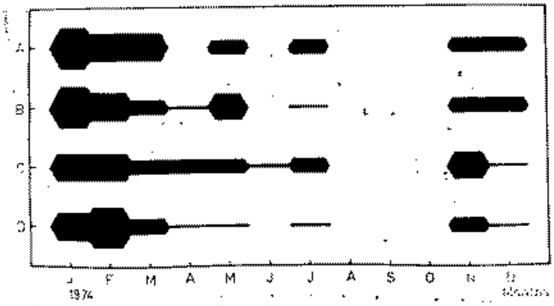
Zoothamnium sp.



Vorticella sp.



Acineta sp.



Gonothyraea inornata + Obelia angulosa

Fig. 9.—Settlement cycles on short-term panels.

cies have presented a pattern of seasonal settlement, with peak intensity during the summer months and interruption between August and October. Since the beginning of fouling studies in 1965, settlement of hydroids has presented marked variations. In some cases, they have exhibited an annual cycle, with dense establishment of colonies at all depths; in others, they have settled seasonally, while during one of the researches they were represented by only a few specimens and then, only for a short period of time (Bastida, 1971 *b*).

Tubularia crocea (fig. 10)

Heaviest settlement of this hydroid took place on panel borders or forming isolated dense clumps on the panel surface. It is a fast-growing species, with a seasonal cycle of settlement which has varied remarkably along the years. In the present study, settlement was confined to the summer months.

Nematodes (fig. 10)

They are very abundant members of local fouling communities. The group is represented by two genera and several species which are considered in one graph, due to the difficulties of quick identification during sample examination. These organisms were consistently encountered throughout the whole year and at all depths; peak settlement coincided with dates of immersion and withdrawal of test panels.

Polychaetes

These organisms are chief components of fouling communities in most harbours of the world. The action of the different species on substrates is of a varied nature; serpulids such as *Mercierella enigmatica, Hydroides elegans* and *H. plateni* may be considered as the most aggressive forms, though during the period 1973/74 they have appeared in no significant amounts with respect to previous years.

Some polychaetes are also good indicators of polluter waters, as is the case of the spionid *Polydora ligni*.

Polydora ligni (fig. 10)

In recent years, this species has become one of the dominant forms in local fouling communities. The first observations on *Polydora ligni* showed an irregular pattern of settlement, and the season of larval colonization varied remarkably from one year to another. This was probably the result of fluctuations in environmental conditions, especially with reference to increasing pollution in the area.

During the present study, *Polydora ligni* has presented a pattern of annual settlement, with heavy growth at all depths and throughout the entire year. Its absence during part of September and October was not apparently related to anomalous environmental conditions and the cause of this fact remains unknown.

The increasing abundance of this species constitutes a serious problem which deserves special attention, particularly on account of its high resistance to the action of organic and inorganic toxics.

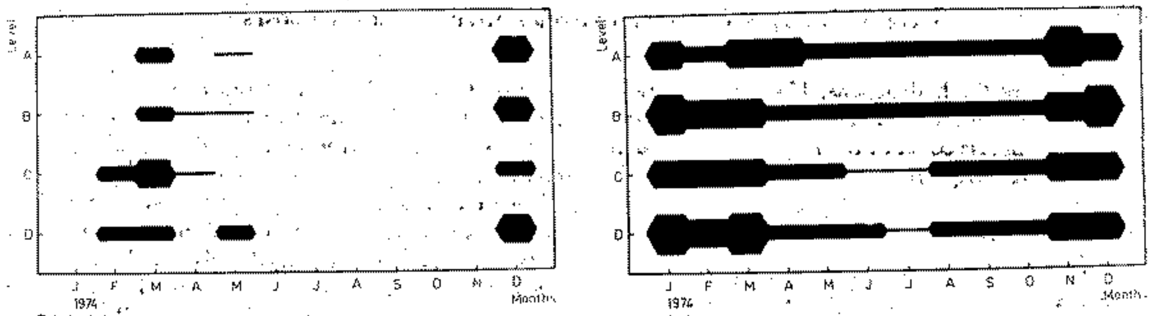
Mollucs

Although mussels — namely *Mytilus platensis* and *Brachydontes rodriguezi* — are typical members of the local midlittoral and sublittoral rocky shore communities, they are infrequent colonizers of test surfaces. This can be attributed, for one part, to the floating condition of the substrate, as well as to the low growth rate of these organisms as compared to other species with which they must compete for space. Moreover, these species seem to require the establishment of a well-developed community prior to settlement, so that they are usually absent from short-term panels and appear only in the long-term series.

Unlike mussels, nudibranchs such as *Tenellia pallida have* been conspicuous forms on test surfaces during the course of this study and in previous years.

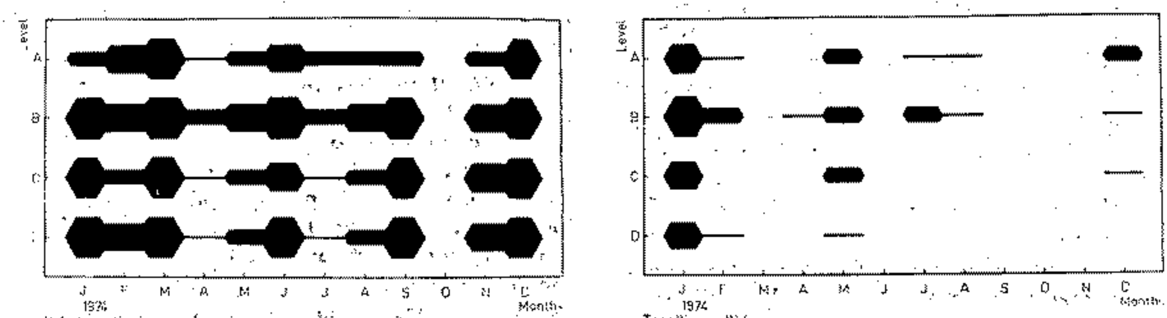
Tenellia pallida (fig. 10)

It has settled seasonally and invariably on panels bearing colonies of *Gonothyraea inornata* and *Obelia angulosa,* which constitute its habitat and food source. Peak intensity of settlement is coincident with the arrival of the first set of campanulariids in December. In addition to the main settling period, light settlements were sporadically recorded during the rest of the year, always associated with the



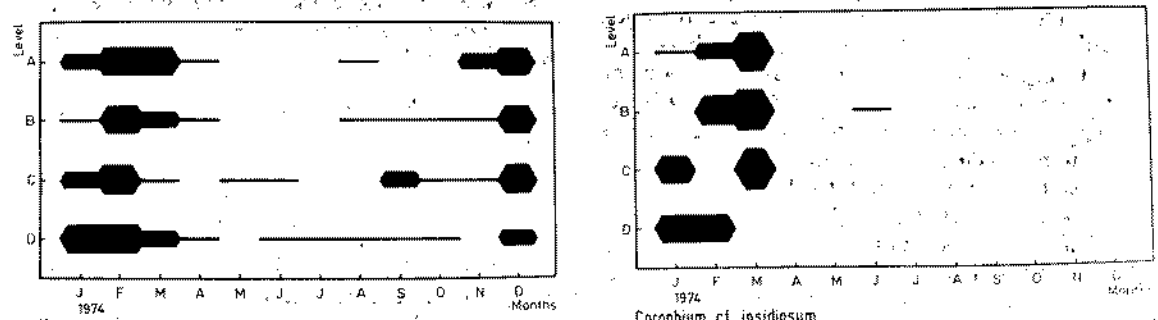
Tubularia crocea

Nematodes



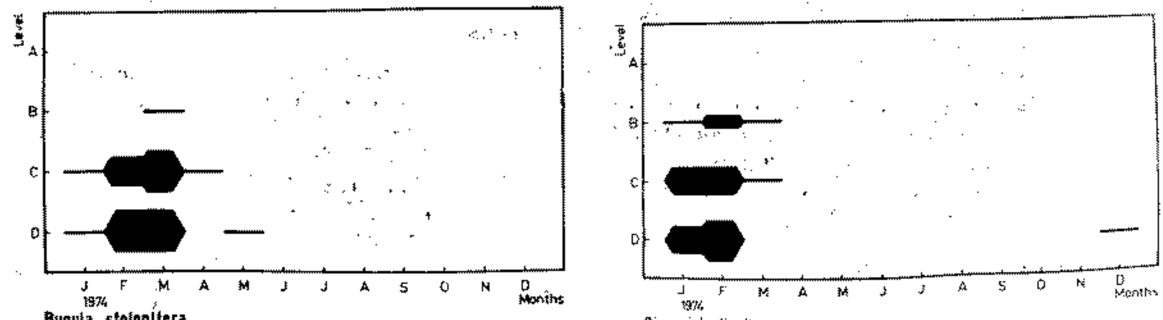
Polydora ligni

Tenellia pallida



Harpacticus pulvinatus + Tisbe gurneyi

Corophium cf. insidiosum



Bugula stolonifera

Ciona intestinalis

FIG. 10.—Settlement cycles on short-term panels.

presence of the hydrozoans. This close relationship between both organisms has been consistently observed since the beginning of studies in the area (fig. 10).

Crustaceans

This greatly diversified group comprises highly deleterious fouling organisms such as barnacles and others having practically no effect on submerged structures. This second category includes free-living amphipods, decapods and harpacticoid copepods which, together with barnacles, are by far the most abundant crustaceans encountered on short-term panels. Barnacles will be considered separately at the end of the chapter.

Harpacticus pulvinatus and *Tisbe gurneyi* (fig. 10)

These are the most frequently encountered harpacticoid copepods on panels at all depths. In the present study, colonization occured from December to March and from November until the end of the experimental period. During the rest of the year, they were recorded only sporadically and in small numbers.

Copepods are particularly abundant during the initial stages of fouling development, feeding on components of the slime film such as diatoms, bacteria and detritus. Moreover, they constitute an important food source for later colonizers, including *Balanus trigonus, Corophium* cf. *insidiosum; Halosydnella australis* and *Mercierella enigmatica:*

Corophium cf. *insidiosum* (fig. 10)

It is the most abundant amphipod of the harbour area. Like other fouling species, its season of settlement has become more extended in recent years, though peak intensity usually coincides with the warm months.

In the present study, colonization was restricted to a period extending from December to March, with no other important settlement occurring during the rest of the year.

Cyrtograpsus angulatus

Due to the fact that it requires a well-developed community to provide a suitable habitat, this species is never significant on short-term panels, except during the summer months. In 1973/74, it was recorded in small numbers from December to February. During past assays, it was found to settle for a few months longer.

The related species *Cyrtograpsus altimanus,* though abundantly represented in previous years, has been encountered only rarely and seems to be disappearing from the harbour area, presumably as a result of local pollution and competition with the isopod *Sphaeroma* cf. *serratum* on the midlittoral level.

Bryozoans

In spite of the fact that bryozoans are prominent fouling organisms in most harbours of the world, they do not play an important part in fouling communities at Mar del Plata and have been particularly poorly represented during the present study. This is not the case of other Argentine harbours, like Puerto Belgrano (38° 54' S, 62° 06' W), where some species clearly dominate certain stages of the community (Bastida and Torti, 1973; Bastida *et al.*, 1974; Bastida and L. de Bastida, 1978).

It should be noted that, unlike other years, *Bowerbankia gracilis* has been absent from the short-term series.

Bugula stolonifera (fig. 10)

This species is occasionally accompanied in the area by *Bugula flabellata,* the latter being always present in low densities.

Bugula stolonifera has settled seasonally, with a main period of colonization from January to March, coinciding with the warm season. It has been absent from the waterline panel (A) and very scantily represented on panel B.

Tunicates

This group is represented in the area by only a few species, but certain populations develop abundantly and are dominant during some stages of fouling development. Ascidian settlement has declined remarkably with respect to other years and was not very intense during the period 1973/74.

Ciona intestinalis (fig. 10)

This simple ascidian typifies the sublittoral benthic communities of the port area. During

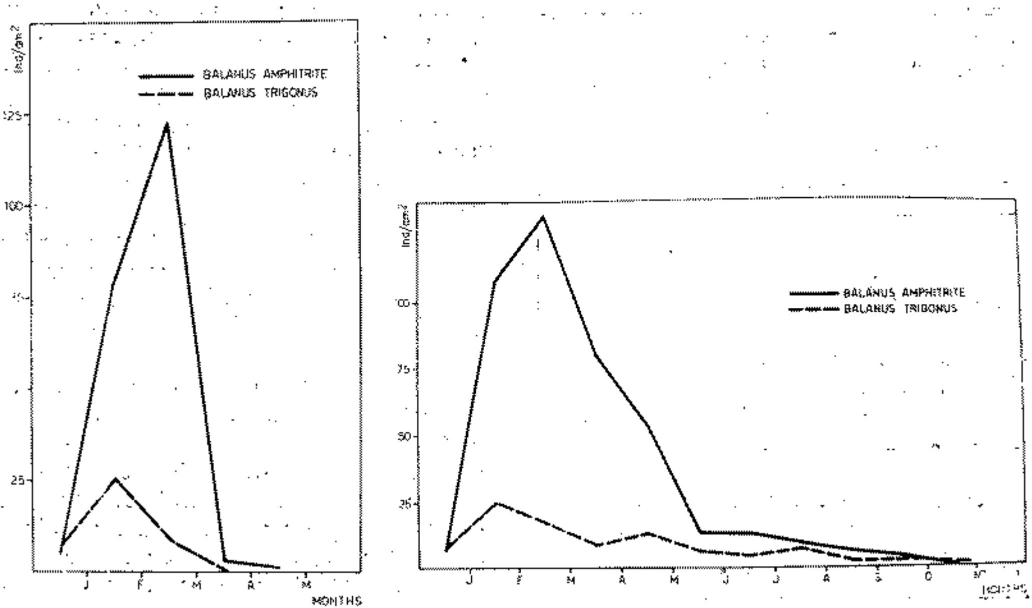


FIG. 11.—*Balanus amphitrite* and *B. trigonus.* Settlement on short-term panels (left) and long-term panels (right); average of values obtained on levels A, B, C and D.

the first fouling studies at Mar del Plata, *Ciona intestinalis* presented an annual cycle of colonization, but in the period 1973/74 it has settled seasonally between December and March and most intensively on the deeper panels.

The shortening of the settlement cycle of this species has greatly modified the successional sequence of development of the community on long-term panels, since *Ciona intestinalis* had always dominated long-established fouling communities.

SOME CONSIDERATIONS ON BARNACLE SETTLEMENT

Special attention has been given to barnacles in view of their great significance as fouling organisms causing serious mechanical damage on submerged structures. Moreover, these organisms are highly resistant to toxics employed in antifouling paints. Specimens settling on both short and long term panels were carefully counted and measured, in order to evaluate the incidence of local barnacle fouling.

Four species have been identified in the harbour area: *Balanus amphitrite, B. trigonus, B. improvisus* and *B. glandula.* Of these, only the first two are conspicuous on test surfaces; *Balanus improvisus* and *B. glandula* are infrequent colonizers of submerged structures, though they seem to be increasing in abundance in the last few years.

Settlement by *Balanus amphitrite* and *B. trigonus* follows a similar pattern and is closely related to prevailing water temperatures. Specimens attached on harbour structures attain sexual maturity in spring; larvae are retained within the mantle cavity and are released only after suitable temperature conditions become established.

In the period 1973/74, *Balanus amphitrite* settled from December to May, while in the case of *B. trigonus,* settlement extended from December to March. During both periods, mean water temperatures ranging from 14.5 to 20° C were recorded. Although initial colonization by both species takes place simultaneously, *Balanus amphitrite* settles for some time longer than *B. trigonus* (figs. 11 and 12). This summer settlement of *Balanus amphitrite* and *B. trigonus* is consistent with Skerman's observations on the two species at the port

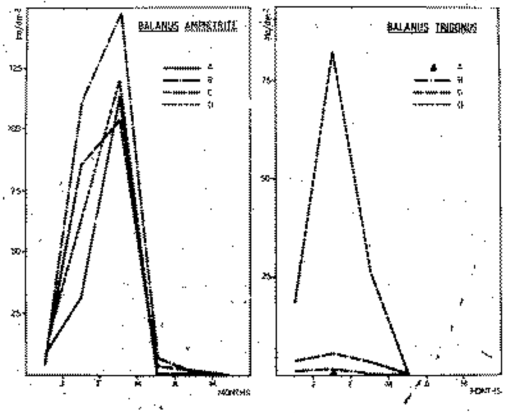


FIG. 12.—*Balanus amphitrite* and *Balanus trigonus*. Settlement on short-term panels at each of the four depth levels.

of Auckland, New Zealand, where settlement takes place between September and March (Skerman, 1959) (figs. 11 and 12).

In the Mar del Plata area, seasons of settlement as well as numerical abundance of barnacle populations have suffered practically no variations along the years (Bastida, 1971 *b*; Bastida and Adabbo, 1975). During the present research, heaviest settlement of *Balanus amphitrite* occurred in mid-February, with a mean density of 122 individuals/dm² (taken as an average of panels A, B, C and D). In the case of *Balanus trigonus*, the highest density was recorded in mid-January with 25.25 individuals/dm² (fig. 11). In tropical areas, both species were found to settle throughout the whole year, though with periods of more intense colonization coinciding with maximum water temperatures (Miyakasi, 1938; Edmonson and Ingram, 1939; Relini and Giordano, 1969).

The number of barnacles settling on test panels has suffered wide monthly variations. Initial colonization was followed by increasingly intense settlement, with a peak during the mid-summer months. By the end of summer, settlement declined sharply (figs. 11 and 12). A similar pattern can be followed in planktonic barnacle larvae, whose density in the mass of water increases until a maximum is reached between January and February. Then follows a marked decline in numerical abundance of larvae which coincides with the lighter barnacle settlement on test panels.

On long-term panels, barnacles remain attached until October-November, though populations decline from May onwards (figs. 11 and 13). This is a clear evidence of the annual renewal of barnacle populations in the port of Mar del Plata.

The pattern of vertical distribution for both species is illustrated in figures 12 and 13. *Balanus amphitrite*, though recorded at all depths, seems to show a certain preference for the shallow panels; *B. trigonus*, on the other hand, tends to settle most abundantly on the deeper panels, mainly on panel D (figure 13).

As has been pointed out in previous papers (Bastida, 1971 *a* and *b*), *Balanus amphitrite* and *B. trigonus* grow at very rapid rates in the Mar del Plata area, mainly as a result of high food availability. Largest specimens of *Balanus amphitrite* attain a size of 12 mm in basal diameter after one month of exposure in January,

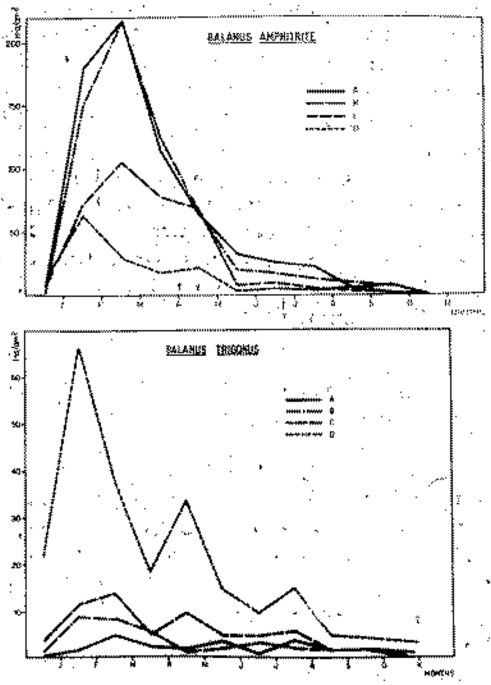


FIG. 13.—*Balanus amphitrite* and *Balanus trigonus*. Settlement on long-term panels at each of the four depth levels.

while those of *B. trigonus* reach 8.5 mm in basal diameter during February.

Theoretical growth-curves of *Balanus amphitrite* and *B. trigonus* (fig. 14) were obtained from monthly size-frequency distributions, using the method proposed by Gulland and Holt (1959). This method has been applied with satisfactory results in studies on other fouling species (Bastida, Capezzani and Torti, 1971). Length of scuta was chosen as a size index, since it proved to be more reliable and less variable than rostro-carinal diameter used by most authors. Asymptote length was found to be 8.04 mm (scutum length) for *B. amphitrite* and 8.18 mm (scutum length) for *B. trigonus*. In both cases, these values coincide fairly well with those obtained from direct examination of specimens on test panels, though the latter tend to be higher than the former.

Growth rate was also found to vary with depth. *Balanus amphitrite* specimens attached on panel D grew much more rapidly than those found on panel A; since populations inhabiting the waterline zone suffer periodical emersions as a consequence of the water movements, which affect their normal feeding activity (fig. 14).

In order to determine the effects of interspecific competition and its influence on vertical distribution of barnacles, a frame carrying two sets of four acrylic panels each was submerged during the same experimental period. In one set, potential competitors for barnacles were removed from all panels every month and the frame was immediately resubmerged. The other set was unaltered and used for reference. At the end of the exposure period, both sets of panels were retrieved and returned to the laboratory for examination. Epizoic growth was removed, exposing the barnacle populations. Finally, barnacles were scraped from the panels and separated for weight evaluation. Clean panels on which basis marks appeared clearly were photographed and these marks were used as an estimate of the area covered by barnacles expressed as a percentage of the total panel surface.

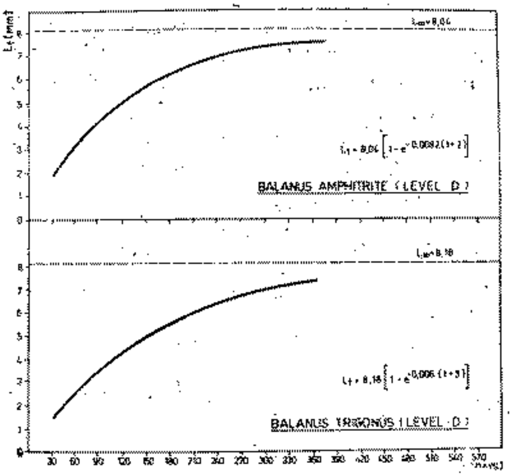


FIG. 14.—*Balanus amphitrite* and *Balanus trigonus*. Growth curves.

Results of this assay indicate that the main competitor of barnacles on the waterline zone has been the green alga *Enteromorpha*. Once the *Enteromorpha* belt, which in some cases attains a width of 5 cm (Bastida, 1971 *a*), has been artificially elliminated, 20 % more of the panel surface appeared covered by barnacles.

The process of invasion of the algal belt by barnacles can also be observed under natural conditions. The limpet *Siphonaria lessoni* grazing upon the algae leaves exposed areas which become rapidly colonized by barnacles (Bastida, Capezzani and Torti, 1971). On the other hand, during periodical declines of *Enteromorpha* populations such as those preceding replacement by red algae, bare areas which become available are immediately invaded by barnacles.

On the deeper panels (B, C and D), *Ciona intestinalis* was found to be the most serious competitor for barnacles. Exposed areas for settlement of barnacle larvae become much reduced by ascidian growth; on the reference panels, no barnacles were found underlying ascidian populations. Moreover, high mortality results from dense overgrowth on barnacles by ascidians and the consequent accumulation of particulate sediment on the panels. Underlying barnacles appear either with empty shells or fall off, only the calcareous basal plates remaining attached to the panel surface. Panel B has exhibited less competitive features; the difference between the area covered by barnacles in both sets was unsignificant (5 %) and almost no mortality was observed.

Intense competition became established on panel C, with 27 % difference in covered area. These results are consistent with the fact that *Ciona intestinalis* grows most intensively on panels C and D.

As a result of spatial competition, numerous cases of epibiosis were recorded, with barnacles growing on *Cyrtograpsus*, *Brachydontes*, *Ulva* and *Enteromorpha* (Bastida, 1971 *a*) and in the present study even on *Ciona*. Specimens growing epizoically on other organisms face rather unstable substrate conditions and they rarely attain large sizes.

EVOLUTION OF THE COMMUNITY ON LONG-TERM PANELS

Most of the available information on the process of ecological succession proceeds from studies on terrestrial plant communities. In the marine environment, these phenomena occur in a rather different manner and it has often been stated that a true succession does not take place. However, observations on sedentary organisms inhabiting submerged objects such as experimental plates have shown a sequence of settlement and subsequent development which constitute a particular case of succession (Bastida, 1971 *a* and *b*).

The present chapter deals with the main stages in the evolution of communities on long-term panels. During the first month of exposure, panels were withdrawn at short intervals in order to detect the establishment of a slime film; monthly samples were obtained throughout the rest of the assay.

Initial fouling settlement coincided with a progressive raise in water temperature, since panels were submerged at the beginning of the warm season (December 18th). After fourty-eight hours of exposure, heavy settlement and growth of bacteria had taken place. Detritus particles associated with further quantities of bacteria accumulated soon after, accompanied by free-living protozoans. Substrate conditions are in this way slightly modified, especially in terms of hardness, texture and pH.

Bacterial settlement was followed by growth of benthic diatoms, mainly *Pleurosigma* and *Synedra;* some planktonic species such as *Skeletonema costatum*, dominant in harbour waters during this period, were also present. The original properties of the substrate are further altered and it becomes rich in food material.

By the tenth day of exposure, food availability in the slime film favoured the arrival of sessile and free-living protozoans which shared dominance with the diatoms, especially on the lower levels. Harpacticoid copepods, rotifers, nematodes and larvae of numerous macrofoulers also made their appearance.

At this stage of fouling development, test panels can be divided in three ecological zones:

1. Top submerged portion of the waterline panel, which can be homologated on the basis of its biological components to the midlittoral level.
2. Inferior submerged portion of the waterline panel and top border of panel B. This zone is inhabited by midlittoral and sublittoral forms, though the latter predominate among adult organisms.
3. Inferior portion of panel B and total areas of panels C and D, with typical members of the sublittoral level and no midlittoral organisms in the adult form.

The upper portion of the surface panel was typified by the presence of an algal belt, consisting mainly of the green algae *Enteromorpha* and *Ulva*. Soon after the establishment of the algal belt, chironomid eggs apeared among the filaments; larvae hatched within a month and grazed upon algae and diatoms.

Barnacle settlement occurred on the area immediately beneath the algal belt, with *Balanus amphitrite* and *B. improvisus* as dominant forms; light settlement of *Balanus trigonus* was restricted to the deeper levels.

The abundance of particulate detritus encouraged the arrival of *Polydora ligni* larvae and the initiation of their tube-building activity. Widespread growth of the hydroids *Obelia angulosa* and *Gonothyraea inornata* was followed by the appearance of the nudibranch *Tenellia pallida,* which feeds exclusively on these hydroids.

The main features of the one-month community were the richness in variety of species and the remarkable growth rate exhibited by some of its components. The filaments of the green alga *Enteromorpha*, for example, attained a length of 28 cm, with an average growth of 1 cm per day. *Balanus amphitrite*, on the other hand, reached a maximum basal diameter of 7 mm, while campanulariid hydroids achieved a height of 2 cm. The community was characterized by the algal belt, consisting mainly of an *Enteromorpha-Ulva*-Chironomidae association; two fouling assemblages, *Balanus amphitrite-B. improvisus-Polydora ligni* and *Obelia angulosa-Gonothyraea inornata-Tenellia pallida* predominated on the lower levels.

The pattern of settlement during the second month was similar to that observed in the preceding month, with the additional appearance of *Siphonaria lessoni* and *Spaeroma* cf. *serratum* on the algae-dominated area. The midlittoral habits of these organisms as well as their trophic requirements account for this depth preference. The simple ascidian *Ciona intestinalis* settled abundantly on the deeper levels.

This period is particularly significant, due to the great intensity of fouling settlement as well as the high growth rate of settled organisms. Biomass figures were almost ten times greater than those recorded during the previous month. Competition for space determined the existence of a clear vertical stratification, with algal fouling predominating in the waterline zone and an area of barnacle settlement which is limited superiorly by algal growth and by the high incidence of *Ciona intestinalis* on the lower levels.

Communities developed after a three-month period showed much resemblance in their constitution to those arising after two months of exposure. Settled organisms, however, have reached maximum sizes, resulting in a high amount of biomass and the establishment of rather stable conditions, similar to those prevailing in neighbouring natural communities. Scattered colonies of the bryozoans *Bugula* and *Conopeum* made their appearance.

By the end of the fourth month, some members of the community had fallen off, with a consequent decrease in weight of fouling growth. On the surface panels, the red alga *Polysiphonia* developed at the expense of the previously dominant green algae. *Polysiphonia* specimens attained a length of 10 cm, while a few persisting *Enteromorpha* filaments measured 9 cm.

During this period, there was no appreciable increase in individual barnacle size and a heavy mortality was registered among barnacle populations. The isopod *Sphaeroma* occupied empty barnacle shells and developed in great numbers, while new colonizing barnacles gradually made their arrival. The *Ciona* and *Polydora* populations suffered a significant decline, a high percentage of individuals having completed their life-cycle. Campanulariid populations, on the other hand, remained stable, although settled organisms grew in size, reaching in some cases a height of 7 cm.

The process of detachment continued throughout the fifth month, leading to the exposure of some areas of the panels which become immediately available for recolonization. A slime film soon appeared on these bare areas, while massive growths of the bryozoan *Bowerbankia gracilis* covered the rest of the panel surface.

By the end of the sixth month, *Polysiphonia* appeared as the dominant form on the waterline level; chironomid larvae were no longer present. The lower panels were dominated by barnacles, hydroids, *Bowerbankia* and *Polydora*.

At the seventh month of exposure, a peak in total biomass was recorded, principally due to high incidence of hydroids, *Bowerbankia* and *Polydora*, as well as appreciable quantities of epizoic growth. Dense tufts of *Tubularia crocea* were present on some areas. The algal belt was once again dominated by *Enteromorpha* and *Ulva* and abundant growth of *Plysiphonia* on the adjacent lower area. A light settlement of *Balanus improvisus* was restricted to the surface panels and continued throughout the eighth month. *Balanus amphitrite* and *B. trigonus* populations suffered a gradual reduction, with great mortality of adult specimens.

No significant changes were registered during the ninth month. In the tenth month, there was a slight decrease in biomass weight. Biomass values then became stable during the eleventh month and this situation persisted until the end of the experimental period (figure 15).

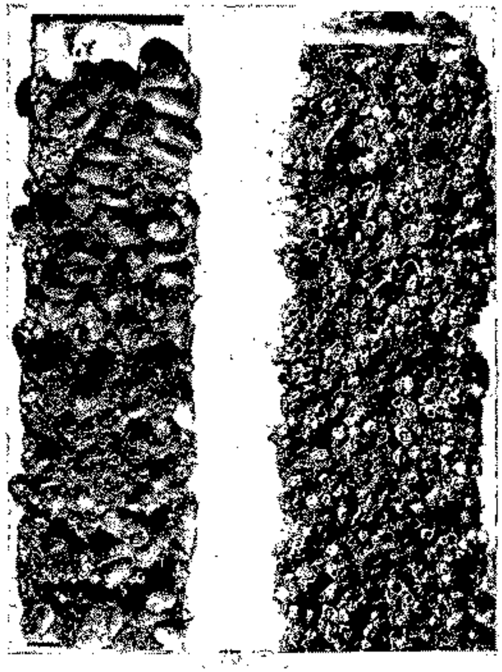


FIG. 15.—Panels showing a fouling assemblage dominated by the ascidian *Ciona intestinalis* (left) and by the barnacles *Balanus amphitrite* and *Balanus trigonus* (right).

CONCLUSIONS

The hydrological characteristics of Mar del Plata harbour during the present period have been similar to those recorded in previous years. Salinity was found to have no influence on fouling development, while low pH values mainly related to local pollution were occasionally recorded.

Data derived from biomass determinations of fouling samples indicate that on short-term panels, fouling biomass is intimatley related to water temperature. The sharp decrease which is registered at the end of March could be attributed to an undetermined environmental anomaly rather than to the effect of temperature variation. On long-term panels, temperature only affects initial settlement of fouling organisms and the first successional stages of the community. Peak biomass values are therefore a result of internal dynamic processes of the community and can even be recorded during the cold months, as in the present study.

Biomass values recorded on long-term panels present certain fluctuations, but sharp declines such as those registered in *Ciona*-dominated communities of previous years were not recorded during this research. On the other hand, biomass data obtained from the short-term series indicate that intense fouling conditions prevail in the Mar del Plata area during the summer months, similar or even more intense than those found in tropical areas.

Attachment seasons of some organisms, for example diatoms, vary widely from one year to another, both in length of time as in numerical abundance of settlers. Some fouling forms present longer cycles of colonization than in previous years, as is the case of the polychaete *Polydora ligni;* others, namely the ascidian *Ciona intestinalis,* have suffered drastic reductions in the length of their seasons of settlement which have modified the ecological sequence of long-term communities. On the other hand, water temperature was found to affect the settlement patterns of some species, like the barnacles *Balanus amphitrite* and *B. trigonus,* while in other cases it seems to have absolutely no influence on these phenomena.

The process of ecological succession as observed on long-term panels was found to comprise the following stages: after a few days of exposure, panels became covered by a well-developed slime film. Within a month, an algal belt became established on the waterline level, dominated by the green algae *Enteromorpha* and *Ulva,* which were eventually replaced by the red alga *Polysiphonia.* The barnacles *Balanus amphitrite* and *B. trigonus,* the polychaete *Polydora ligni* and the hydroids *Obelia angulosa* and *Gonothyraea inornata* shared dominance on the deeper panels.

Balanus amphitrite and *B. trigonus* proved to be the most common barnacles encountered on test panels and the most aggressive local fouling organisms. Settlement of these species is intimately related to water temperature and has presented practically no variations along the years. Growth rate is also influenced by temperature and during the hot months, specimens reach similar sizes as those inhabiting tropical waters.

TABLE 1

LIST OF SPECIES RECORDED ON TEST PANELS AT THE PORT OF MAR DEL PLATA SINCE 1965

ALGAE

Bacillariophyta

Actinoptichus sp.
Achnantes longipes
Amphora sp.
Asterionella japonica
Bacillaria sp.
Biddulphia aurita var. *obtusa*
Biddulphia chinensis
Biddulphia mobiliensis
Chaetoceros sp.
Cocconeis sp.
Coscinodiscus sp.
Ditylum brightwellii
Fragilaria sp.
Grammatophora marina
Grammatophora sp.
Licmophora abbreviata
Melosira sulcata
Melosira sp.
Navicula grevillei
Navicula spp.
Nitzschia closterium
Nitzschia longissima
Nitzschia seriata
Opephora sp.
Pinnularia sp.
Plagiogramma sp.
Pleurosigma sp.
Rhizosolenia sp.
Skeletonema costatum
Stephanopyxis turris
Synedra sp.
Thalassionema nitzschioides
Thalassiosira decipiens
Thalassiotrix frauenfeldii
Thalassiotrix nitzschioides
Triceratium favus

Cyanophyta

Lyngbya lutea
Microcoleus tenerrinus
Phormidium corium

Chlorophyta

Bryopsis plumosa
Cladophora sp.
Enteromorpha flexuosa
Enteromorpha intestinalis
Enteromorpha prolifera
Ulothrix pseudoflacca

Phaeophyta

Ectocarpus confervoides
Petalonia fascia

Rhodophyta

Bangia sp.
Callithamnion sp.
Ceramium sp.
Erythrocladia sp.
Polysiphonia sp.
Porphyra umbilicalis
Pterosiphonia sp.

MOLLUSCA

Buccinanops sp.
Brachydontes rodriguezi
Chaetopleura tehuelcha
Mytilus platensis
Pyrene isabellei
Pyrene paessleri
Polycera marplatensis
Saxicava solida
Siphonaria lessoni
Tenellia pallida

PYCNOGONIDA

Achelia assimilis
Anoplodactylus petiolatus
Anoplodactylus pigmaeus
Anoplodactylus stictus
Tanystylum orbiculare

TABLE 1 (Continued.)

CRUSTACEA

Copepoda

Harpacticus pulbinatus
Harpacticus sp.
Heterolaophonte pauciseta
Paraltheuta minuta
Paralaophonte meinerti
Robergurneya falklandiensis
Tisbe gurneyi

Isopoda

Idotea baltica
Sphaeroma cf. *serratum*

Amphipoda

Caprella dilatata
Corophium cfr. *insidiosum*
Hyale sp.
Jassa sp.

Cirripedia

Balanus amphitrite amphitrite
Balanus glandulfa
Balanus improvisus
Balanus trigonus

Decapoda

Cyrtograpsus altimanus
Cyrtograpsus angulatus
Coenophthalmus tridentatus
Pachycheles haigae
Pelia rotunda
Pilumnoides hassleri
Platyxanthus crenulatus

INSECTA

Chironomidae (larvae)

TUNICATA

Botryllus schlosseri
Ciona intestinalis

Didemnidae

Molgula manhattensis
Molgula cf. *occidentalis*
Molgula robusta
Styela plicata

PISCES

Gobiosoma (Austrogobius) parri
Hypleurochilus fissicornis
Ribeiroclinus eigenmanni

PROTOZOA

Dinoflagellata

Ceratium sp.
Dinophysis sp.
Exuviaella sp.
Goniodoma sp.
Peridinium sp.
Prorocentrum sp.

T A B L E I (Continued.)

Silicoflagellata
Dictyocha sp.

Ciliata

Claustrofolliculina sp.
Codonella sp.
Colpidium sp.
Condylostoma sp.
Cothurnia sp.
Euplotes sp.
Favella sp.
Frontonia sp.
Helicostomella sp.
Lacrymaria sp.
Lagotia sp.
Mesodinium sp.
Petalotricha sp.
Tintinnopsis sp.
Tintinnus sp.
Trachelonema sp.
Vorticella sp.
Zoothamnium sp.

Suctoria

Acineta sp.
Ephelota sp.
Podophrya sp.

Rhizopoda

Amoeba sp.
Bolivina sp.
Elphidium sp.
Quinqueloculina sp.

COELENTERATA

Gonothyraea inornata
Obelia angulosa
Ramirezia balsaea
Tubularia crocea

PLATHELMINTHES (unidentified)

NEMERTINA (unidentified)

ROTIFERA

Colurella sp.
Trichocerca sp.

ANNELIDA

Cirratulus cirratus
Dorvillea sp.
Eulalia sp.
Halosydnella australis
Hydroides elegans
Hydroides plateni
Lumbrinereis sp.
Mercierella enigmatica
Polydora ligni
Serpula sp.
Stauronereis sp.
Syllidea armata
Syllis gracilis
Syllis robertianae
Thelepus sp.
Tiposyllis prolixa

BRYOZOA

Bowerbankia gracilis
Bugula neritina
Bugula flabellata
Bugula stolonifera
Conopeum sp.
Cryptosula pallasiana

The growth curve equation obtained by the modal displacement of monthly length-frequency distribution, previously decomposed in normal components (structural modes), is

$L_t = 8.04 \ \ 1 - e^{-0.0082\,(t+2)}$ for *Balanus amphitrite,* and
$L_t = 8.18 \ \ 1 - e^{-0.006\,(t+3)}$ for *B. trigonus.*

An analysis of spatial competition in long-established communities based on a particular assay with *Balanus amphitrite* and *B. trigonus* showed that on the waterline level, competition is exerted mainly by the grean alga *Enteromorpha,* whose presence reduces barnacle settlement in approximately 20 %. On deeper panels, attachment of barnacles is reduced mainly by growth of *Ciona intestinalis* in 5 to 27 % (panels B and C respectively).

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PRELIMINARY SHIPS' TRIALS OF CHLORINATED RUBBER ANTIFOULING PAINTS

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INTRODUCTION

Up to now, antifouling paints have been the most adequate method of controlling the settlement of organisms on ships' hulls.

In practice, their main drawback is the loss of toxicant that takes place during navigation and which does not have an effective action on fouling, as this adheres only when the ship is anchored in port or when it navigates at speeds below 4-5 knots. For this reason it has not been possible so far to obtain products whose effectiveness endures for periods of more than two years. This protection period is shorter than that of modern anticorrosive painting systems for the underwater part of the hull.

The enlargement of the intervals between drydockings and the maintaining of vessels free from corrosion and fouling problems are the current targets of technological research on this subject.

In previous stages the authors have developed antifouling formulations of the oleoresinous type of high toxicity. They were determined by means of tests on ships (1, 2) and experimental rafts (3, 4, 5).

The studies currently underway are aimed at obtaining antifouling paints based on a chlorinated rubber binder, which show not only great effectiveness and bioactivity, but also excellent adhesion on marine anticorrosive primers prepared with different pigments.

This resin is being now used in the paint industry particularly, because the film, when correctly plasticized, has excellent resistance to chemical agents, the paints are easy to apply and the film dries quickly. In the case of anticorrosive formulations, chlorinated rubber paints provide an excellent barrier against water and oxygen.

VARIABLES STUDIED

On the basis of previously obtained results on panels exposed on experimental rafts (6) two series of tests were planned, the first one on the hull of three destroyers and the second on a light destroyer and a destroyer.

This preliminary report refers only to the results of the first series of tests.

Paints of different chlorinated rubber/Rosin WW ratios were tested mainly to establish the solubility of the matrix in sea water, the importance of the total toxicant content on the bioactivity of the film, the toxicant/extender ratio and the influence of the use of different plasticizers.

In order to reduce the tests variables to a minimum, four of the vessels used were destroyers which have similar operational and speed characteristics and navigation and port anchoring periods. On the other hand, the light destroyer is a vessel that navigates during shorter periods.

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* CIDEPINT, Research and Development Centre for Paint Technology. Actual address: 52, 121 y 122, 1900 La Plata, Argentina.

The aforementioned vessels are usually anchored at Belgrano's Harbour (38° 58' S, 62° 06' W) and navigate in the South Atlantic. The light destroyer is usually anchored at Mar del Plata's Port (38° 08' S, 57° 31' W) and is a support vessel for the ships that operate from the latter harbour.

The tested paints were applied over oleoresinous anticorrosive systems, with and without the use of intermediate paint (phenolic resin-chlorinated rubber type).

TABLE I

COMPOSITION OF THE ANTIFOULING PAINTS TESTED (g/100 g)

	PAINTS*									
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Cuprous oxide ...	54.4	43.5	32.6	21.7	10.9	54.7	43.7	32.8	21.9	10.9
Zinc oxide	5.4	4.3	3.3	2.2	1.1	5.4	4.4	3.3	2.2	1.1
Whiting ($CaCO_3$).	—	12.0	23.9	35.9	47.8	—	12.0	24.0	36.0	48.1
Plasticizer ** ...	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
Binder (solids) ...	13.4	13.4	13.4	13.4	13.4	13.5	13.5	13.5	13.5	13.5
Solvents	22.9	22.9	22.9	22.9	22.9	22.5	22.5	22.5	22.5	22.5

* Paints 1 to 5, Rosin WW/chlorinated rubber ratio 1/1 (W/W); paints 6 to 10, Rosin WW/chlorinated rubber ratio 2/1 (W/W).

** Tricresyl-phosphate (ARA "Bouchard", paints 1/10), chlorinated paraffin 42 per cent (ARA "Storni", paints 11/20) or chlorinated byphenil (ARA "Seguí", paints 21/30).

1. Composition variables

a) *Toxicant content*

Cuprous oxide was used as fundamental toxicant; zinc oxide was employed as reinforcing toxicant in all the samples.

The cuprous oxide content in the different formulations (table I) varies between 54.4 and 10.9 %, W/W, on the paint; four of the samples have high toxicant level (paints 1, 2, 6 and 7 of each series), another four can be considered as having a medium level of bioactive material (samples 3, 4, 8 and 9). Finally, the samples 5 and 10 are of low content.

b) *Extender content*

Reduction of toxicant was carried out using an extender. Calcium carbonate (whiting) was employed due to the excellent results obtained in previous experiments (1, 2, 7, 8). The different formulations have whiting contents which vary between 0 and 48 % (W/W) on the paint.

c) *Matrix solubility*

The bioactivity of the antifouling paints is based on the solubility of Rosin WW in sea water of pH 8-8.2. As a result of this dissolution a thin layer with high toxicant concentration is formed closely connected with the painted surface, that is lethal to fouling organisms.

The dissolution speed of Rosin WW is controlled in our formulations by using chlorinated rubber 20 cP. adequately plasticized. Rosin WW/chlorinated rubber 1/1 and 2/1 ratios have been tested (paints 1 to 5 and 6 to 10, respectively, in each series). The last ratio is the one that provides the matrix of highest solubility.

d) *Influence of the type of plasticizer*

The chlorinated rubber films are very brittle and have poor adhesion, from what it is necessary to incorporate plasticizers in the formulations.

The type and chemical characteristics of the plasticizer can influence the following properties: flexibility, chemical resistance of the film, permeability to oxygen and water, etc. Referring to antifouling paints only flexibility is important, thus allowing the use of different types of plasticizers. The paints of the first series (ARA «Bouchard») were plasticized with tricresyl-phosphate; chlorinated paraffin 42 % was used in the second series (ARA «Storni») and chlorinated byphenyl in the third series (ARA «Seguí»). Tricresyl-phosphate can be considered a saponifiable type plasticizer; the other two are inert from the chemical point of view. All the plasticizers employed are compatible with the two resins used in the formulations (Rosin WW and chlorinated rubber).

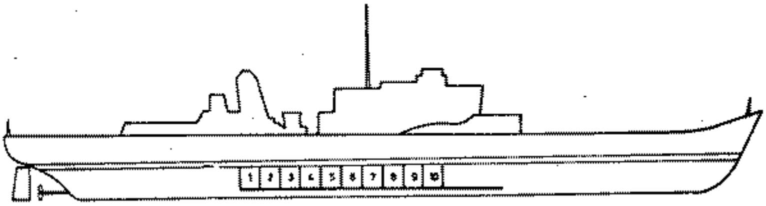

Fig. 1.—Order of the panels painted on the starboard side of the destroyer ARA "Bouchard" (plasticizer tricresyl-phosphate) and "Storni" (plasticizer chlorinated paraffin).

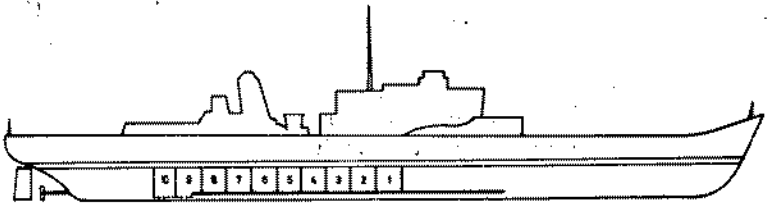

Fig. 2.—Order of the panels painted on the starboard side of the destroyer ARA "Seguí" (plasticizer chlorinated byphenil).

It is necessary to point out that the chlorinated byphenyl is a toxicant substance. It was employed in this work but it must be established that the authors do not promote its use.

2. Variables of hull painting

a) *Selected vessels and location of the panels*

The tests which are the subject matters of this report were carried out on the aforementioned destroyers (ARA «Bouchard», «Storni» and «Seguí»).

As it was previously mentioned, the ARA «Bouchard» navigated during the experimental period in the South Atlantic. It was normally anchored at Belgrano's Harbour besides spending approximately 20 days in a port in Brasil, an area where fouling is very aggressive. The other two destroyers also navigated during rather long periods and the rest of the year remained anchored at Belgrano's Harbour.

The paint samples were placed inversely on both sides (port side and starboard side) of the destroyers. The panels so prepared covered an area of approximately 200 square meters, i.e. 10 square meters by sample. In all the cases the application was made from the water line to the anti-roller wings. Figures 1-2 shows the location of the painted panels on the vessels.

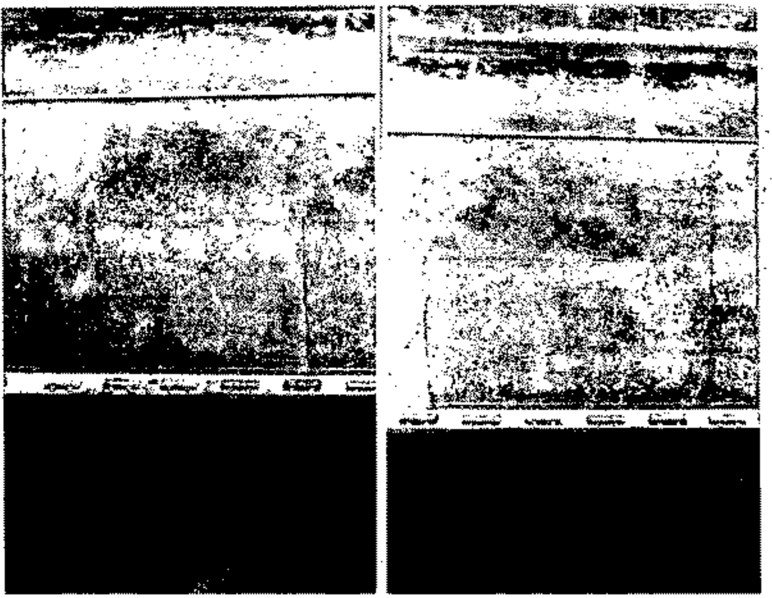

FIG. 3.—Paints 7 (left) and 8 (right) after 23 months immersion (starboard side of the destroyer ARA "Bouchard", plasticizer tricresyl-phosphate.

b) *Experimental periods*

The immersion periods of the three destroyers are shown in table II. Their length depends exclusively on the dates set by the Navy for drydocking. Normally this operation is carried out every 18-24 months. It can happen, however, that a test may have to be interrupted long before the target date due to the necessity of emergency repairs. This happened in the case of the ARA «Storni», whose tests only lasted 9 months.

The destroyer ARA «Seguí», because of similar circumstances, was able to be inspected on two opportunities, 9 and 18 months after starting the test.

The ARA «Bouchard» was observed after a 23 months immersion period.

The periods of intense fouling included in each tests are also shown in table II.

PREPARATION OF THE PAINTS

The paints were prepared on a pilot plant scale using ball mills with jars of 28 liter of capacity for the dispersion of the toxicants in the binders.

Binders preparation was carried out dissolving Rosin WW and chlorinated rubber in adequate solvents and incorporating the required quantities of plasticizers (tricresyl-phosphate, chlorinated paraffin or chlorinated byphenyl) to ensure good flexibility of the film.

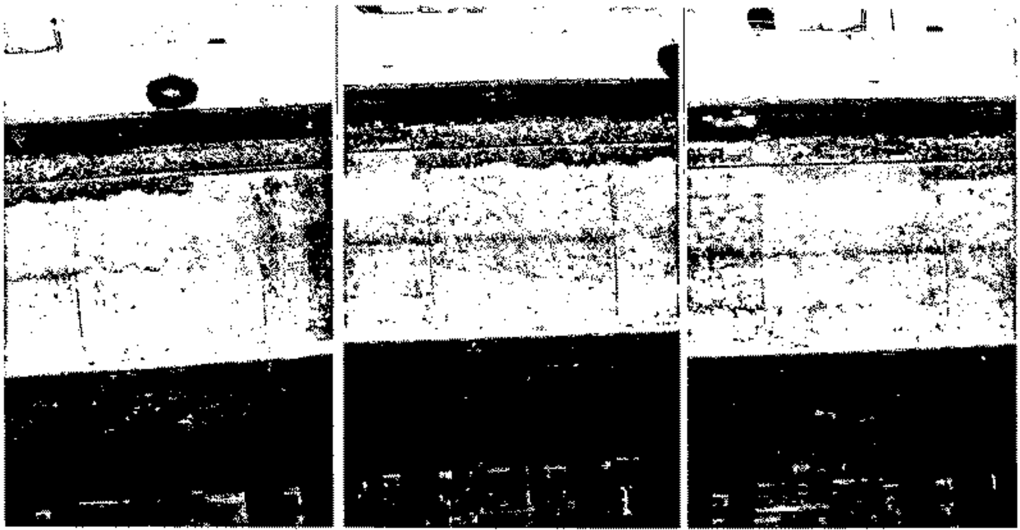

FIG. 4.—Paints 22 (left), 23 (center) and 24 (right) after 18 months immersion (port side of the destroyer ARA "Seguí", plasticizer chlorinated byphenyl).

TABLE II

IMMERSION PERIODS OF THE DIFFERENT SHIPS

	Starting date	*Completion time*	*Immersion time (months)*	*Period of intense fouling (summer)*
Destroyer ARA "Bouchard" ...	September 1977	August 1979	23	2
Destroyer ARA "Storni"	December 1977	August 1978	9	1
Destroyer ARA "Seguí", 1st check-up	March 1978	December 1978	9	—
Destroyer ARA "Seguí", 2nd check-up	March 1978	September 1979	18	1

TABLE III

FOULING SETTELEMENT

Paints	1	2	3	4	5	6	7	8	9	10
Destroyer ARA "Bouchard", 23 months:										
a) Port side	0-1	0-1	1	1	1	0-1	0-1	1	1	0-1
b) Starboard side	1	0	0-1	0-1	1	0	0	0-1	0-1	0-1
Paints	11	12	13	14	15	16	17	18	19	20
Destroyer ARA "Storni", 9 months:										
a) Port side	0	0-1	0-1	0-1	0-1	0	0	0	0	1-2
b) Starboard side	0	0	0-1	0-1	0	0	0	0	0	0-1
Paints	21	22	23	24	25	26	27	28	29	30
Destroyer ARA "Seguí", 1st. check-up, 9 months:										
a) Port side	0-1	0	0	0-1	0-1	0-1	0-1	0	0-1	0-1
b) Starboard side	0	0	0	0	0	0	0	0	0	0-1
Destroyer ARA "Seguí", 2nd. check-up, 18 months:										
a) Port side	0-1	0	0	0	0	0	0	0	0	0
b) Starboard side	0	0	0	0	0	0	0	0	0-1	0-1

Key of the table: 0, without settlement; 0-1, very rare; 1, rare; 2, common; 3, very common; 4, abundant; 5, panel completely fouled.

RESULTS OBTAINED

The chlorinated rubber paints studied in this report were all of the soluble matrix type. The dissolution of Rosin WW was regulated by the presence of chlorinated rubber and the plasticizer allows the release of the toxic material and its action on the animal and vegetable organisms of fouling.

The leaching rate of the antifouling paint will be greater as the matrix becomes more soluble, but the service durability of the paint will be lesser. It is important to remark that once the necessary toxicant solubility is achieved, the leaching rate of the paint must be kept constant while toxicant reserves remain in the film. Environmental conditions are very important because a pH reduction can affect the solubility of Rosin WW and thus block the normal action of the antifouling formulation.

Service trials, specially on ships with long periods of navigation, ensure that the paints will be maintained in areas of low contamination, which assure their normal solubilisation and the elimination of insoluble rests of the matrix (i.e. chlorinated rubber resin) or the reaction products between Rosin WW with calcium and magnesium salts present in sea water.

The above considerations explain the uniformity of the results obtained even for different toxicant concentration and experimental periods of immersion ranging from 9 to 23 months.

Excepting paint 20, applied on the port side of the destroyer ARA «Storni» (settlement 1-2), in all the cases the fouling records were 0 (without settlement), 0-1 (very rare) and 1 (rare) (table III).

It will be noticed that:

a) The different solubility of the matrix (Rosin WW/chlorinated rubber ratios 2/1 and 1/1) does not influence in the bioactivity of these products in the experimental conditions and all the paints have an adequate initial and constant leaching rate.

b) The amount of bioactive material which varies largely for the different samples of each series do not influence the fouling attachment. The paints with minimum toxicant content were practically not fouled.

c) The plasticizers used (tricresyl-phosphate, chlorinated paraffin or chlorinated byphenyl) allow to obtain antifouling paints with similar behaviour, for the different toxicant levels and matrix solubilities.

Some of the antifouling paints tested, at the end of the immersion period, show poor adhesion over the oleoresinous antifouling paint employed by the Navy. For this reason, in the second experimental stage of this work the use of intermediate paints was considered.

The chlorinated rubber antifouling paints studied have a higher leaching rate for copper than the minimum required to ensure fouling control for ships of the Argentine Navy in experimental periods ranging from 9 to 23 months. Navigation of the vessels at high speeds (destroyers) does not affect the durability in service of the paints. The formulations tested show good resistance to the erosive effects of water movement, the paints desintegrate slowly to permit the solubilization of the toxic material and it is not necessary to establish a compromise between toxicity and durability.

The results obtained indicates that the useful life of the paints can be extended well beyond two years, comprising up to three periods of intense fouling attachment in temperate waters. Raft tests carried out previously would seem to confirm this possibility.

It is important to establish that in the case of soluble matrix antifouling paints, durability is proportional to film thickness. In our experiencies thickness ranges between 80 and 100 μm and it could be increased modifying the paint's composition with the incorporation of thixotropic substances.

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MARINE ALGAL FOULING COMMUNITIES ON FLOATING STRUCTURES IN THE SOLENT (SOUTH COAST OF ENGLAND)

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INTRODUCTION

Marine algae are widely regarded as important fouling organisms and have been commonly found attached to the upper, illuminated regions of a wide variety of immersed artificial structures throughout the world. These include both fixed structures such as drilling platforms (Freeman, 1977; Eikers, 1978; Goodman and Ralph, 1979; Ralph and Goodman, 1979) ship wrecks (Lyle, 1926, 1929), pilings, sea walls, break-waters and embankments, etc. (Anand, 1937; Bastida, 1968, 1972; Haderlie, 1977; Van den Hoek, 1958), as well as a wide variety of floating structures such as buoys (Caspers, 1952; Fraser, 1938; Grieve and Robertson, 1864; Hutchins, 1944; Lodge, 1949; Milne, 1940), pontoons (Tittley and Price, 1977) and ships in service (Christie, 1973; Harris, 1943, 1946; Hentschel, 1923; Orton, 1930). Artificial test panels/blocks which are commonly used for monitoring settlement periods/seasonal distribution of organisms and to provide controls for the testing of potential antifouling paints are also frequently colonised by marine algae, especially if the panels are suspended in the surface waters from floating structures such as rafts and pontoons; programmes of test panel immersion, which have reported the presence of marine algae, include Anon. (1966), Banoub (1960), Bruce (1977), Fletcher (1974), Fry (1975), Ghobashy (1977), Greene and Morton (1971), Haderlie (1968 *a*), Harris (1946), Hendey (1951) and Kawahara (1962).

Although an increasing number of reports are drawing attention to fouling problems caused by the presence of algae on fixed structures (Eikers, 1978; Freeman, 1977; Goodman and Ralph, 1979; Leitch, 1980; Pipe, 1980; Ralph and Goodman, 1979) it is their presence on floating structures, particularly ships in service which has caused the most concern over recent decades. The physiological tolerance of some algal genera such as *Ectocarpus* and *Enteromorpha* (see Goodman and Russell, 1976) has resulted not only in their colonisation of the unstable water line area but very often in their dominance over animals on the hulls of many of the faster commuting ocean going vessels (see Christie, 1973). Despite the importance of algae as major colonisers of floating type structures, very few ecological studies have been carried out on the attached fouling communities. Around the British Isles (see Table 1) only four investigations have been carried out on ships in service (Harris, 1943, 1946; Orton, 1930; Christie, 1973) whilst only three detailed studies have been made on the algal composition of buoys (Grieve and Robertson, 1864; Lodge, 1949; Milne, 1940). Also, in most of these studies, only lists of fouling algae are presented with some indication of their relative abundance; Milne (1940), however, does additionally consider some aspects of the structure of the algal communities studied. Although fouling algae are quite comprehensively treated in a number of immersed test panel studies (see especially Fletcher, 1974; Fry, 1975; Harris, 1946; Stubbings and Houghton, 1964) no information is available on aspects of the algal community colonising the unstable water line area.

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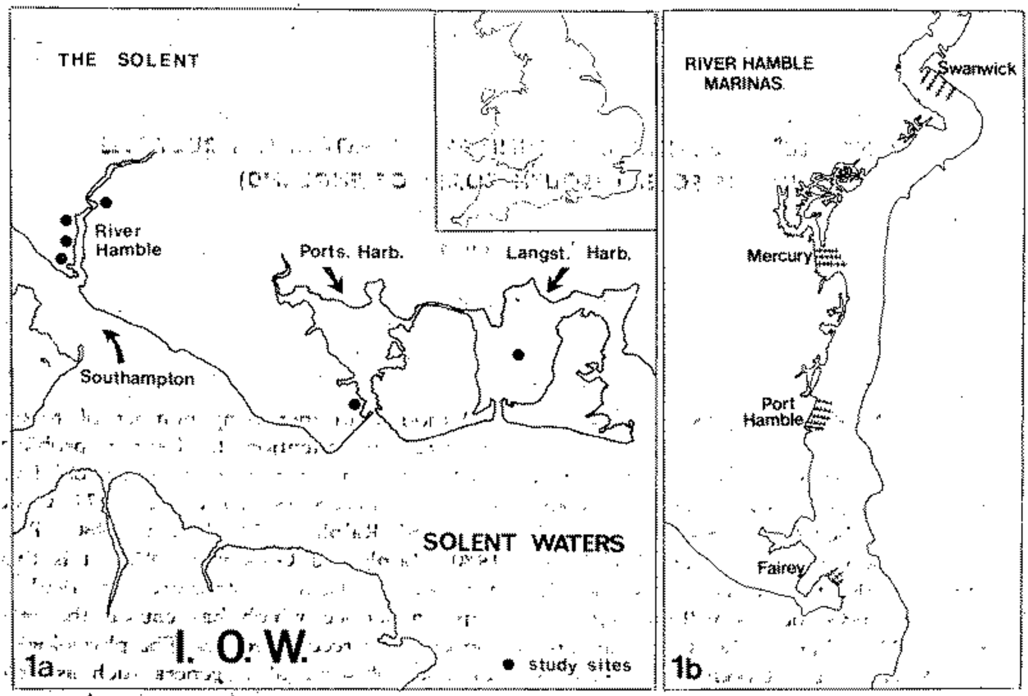

FIG. 1.—1 *a*: Location of study sites. 1 *b*: Distribution of marinas in the River Hamble.

The present paper describes the results obtained from a preliminary survey of the composition of marine algal fouling communities occurring on the sides of various floating pontoons and rafts in the Solent, south coast of England. Particular attention has been focussed on the structure of the algal communities occupying the unstable waterline area, and how this is influenced by various environmental factors such as the degree of exposure to wave action, season of year and the salinity level of the water.

SITES INVESTIGATED

Three locations were chosen for experimental sites viz. Langstone Harbour, Portsmouth Harbour and the river Hamble (see Fig. 1).

(1) LANGSTONE HARBOUR

Langstone Harbour, situated in the north east Solent region, is the central one of three very similar interconnecting natural harbour systems (Fig. 1 *a*). The harbour is almost completely land locked, with two relatively narrow channels connecting the broad northern part to both Portsmouth Harbour in the west and Chichester Harbour in the east, with a further narrow channel connecting the southern part with the Solent waters. The harbour is large (19.4 km²), sheltered, quite shallow, not exceeding 10 m in depth, with an intertidal zone composed predominantly of mudflats and sands and some harbour installations. The tidal range varies between 1.5 m (neaps) and 4.5 m (springs), with tidal stream currents reversing with the tide, ranging from 2.50 km/h (neaps) to 4.64 km/h (springs) (Houghton, 1959). The harbour is fully marine, with surface water salinities recorded during 1978/79 ranging from 30.7 % to 34.3 % (Table 2). Surface water temperatures recorded between 1977-1979 reveal considerable seasonal differences ranging from 2.0° C (February 1979) to 18.3° C (August 1977). Water transparency is generally poor, usually between 1-3 m. Although in-

TABLE 1

INVESTIGATIONS OF MARINE FOULING ORGANISMS ON FLOATING STRUCTURES AROUND THE BRITISH ISLES

Authors	*Date*	*Locality*	*Structure*
Grieve & Robertson	1864	Clyde Sea Area	Buoys
Orton	1930	Plymouth	Pontoons, Rafts, Buoys, Ships' Test surfaces
Fraser	1938	Mersey Est., Liverpool Bay	Buoys
Milne	1940	Tamar Est. (Plymouth)	Buoys
Harris	1943	Various	Ships
		Millport	Test surfaces
Harris	1946	Various	Ships
		Millport	Test surfaces
Corlett	1948	Mersey Est.	Buoys, Pontoons, Rafts
			Test surfaces
Lodge	1949	Port Erin/I.O.M.	Buoys
Hendey	1951	Chichester Harbour	Test surfaces
Stubbings & Houghton	1964	Chichester & Langstone Harbours	Test surfaces
Anon	1966	Poole & Langstone Harbours	Test surfaces
Meadows	1969	N. E. coast	Test surfaces
Christie	1973	Various	Ships
Fletcher	1974	Poole & Langstone Harbours	Test surfaces
Fry	1975	Menai Straits, N. Wales	Test surfaces
Tittley & Price	1977 (a)	Rivers Thames/Medway	Pontons
Tittley & Price	1977 (b)	River Thames	Pontoons
Withers & Thorp	1977	Langstone Harbour	Test surfaces

dustrial pollution is light, the harbour does receive a large (40,000,^{3}) daily discharge of treated sewage effluent in its upper regions.

The floating structures examined consist of a small number of Ministry of Defence Paint Trial Rafts moored centrally in one of the main drainage channels of the Harbour (Figure 2 *a*). The rafts measure 14 m × 7 m and are constructed of a number of air filled metal tanks enclosing an inner central basin into which the panel frames are immersed (Figure 2 *b*). A double chain — mooring at the bow end only, allows the rafts to continually turn and face oncoming currents (2 *c*). Examination was made of the algal communities colonising the vertical non-toxic painted metal sides of 3-4 year immersed rafts. Three main areas were investigated which differed in their relative exposure to wave and current action; the inner, very sheltered walls of the central basin.

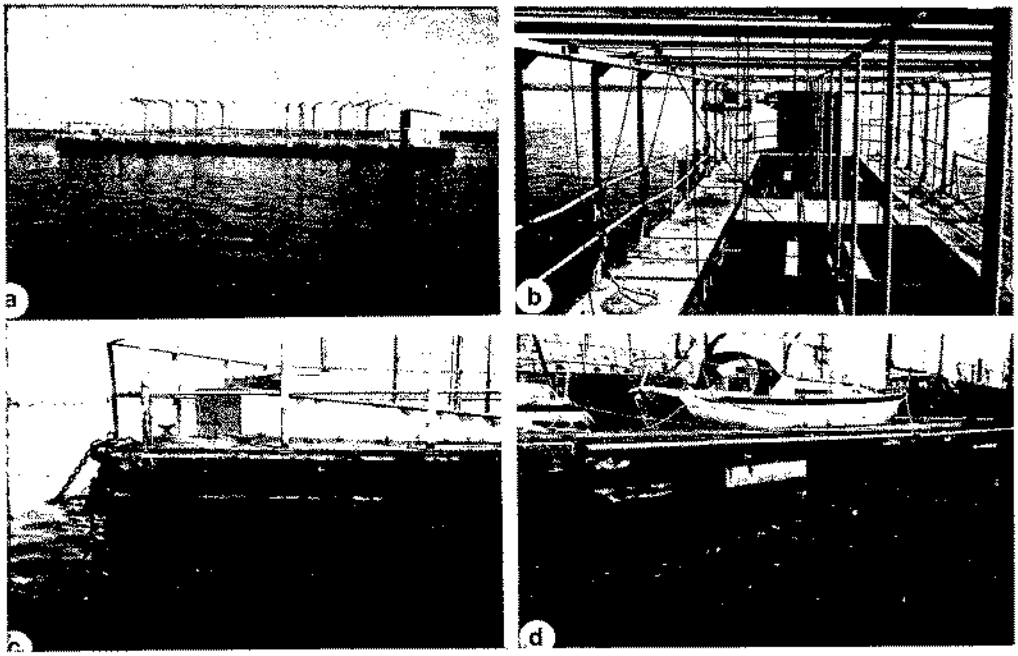

FIG. 2.—*a)* Ministry of Defence Paint Trial Raft in Langstone Harbour. *b)* Inner basins of raft. *c)* Bow end of raft showing upper wave washed algal community. *d)* Gosport Marina pontoon with support "floats".

the outer, more exposed mid region walls and the very exposed, outer bow region walls.

(2) PORTSMOUTH HARBOUR

Hydrologically Portsmouth Harbour is very similar to that of Langstone (Table 2). Situated due west of Langstone Harbour (Fig. 1 *a*), it is similar in size, largely landlocked except for narrow connecting channels at its north-eastern and southern boundaries, fully marine, shallow, turbid and with quite strong tidal currents. It differs slightly from Langstone in that sewage pollution is light and the southern shore-line region is composed of considerable expanses of dockyard installations.

The floating structures examined consist of 3-4 year immersed «floats» supporting an extensive interconnecting system of pontoons constituting the Gosport Marina situated in the south west corner of the Harbour (Fig. 2 *d*). The pontoons, which extend out in a north east direction, vary in their degree of exposure; the inner pontoons are usually very sheltered whilst the outer pontoons are more exposed to wave wash from passing ships and tidal streams. The «floats» under investigation are constructed of untreated concrete covered blocks of polystyrene, partly immersed in the water. Observations were made on the algal communities colonising the vertical sides of the more «unshaded» end floats associated with both the inner, sheltered pontoons and the outer, more exposed pontoons.

(3) RIVER HAMBLE

Investigations were carried out at four sites in the estuarine waters of the river Hamble which flows out into the lower regions of Southampton water (Fig. 1 *a*). The tidal range is similar to that recorded for Langstone Harbour, with maximum tidal stream currents varying between approximately 1.6 km/h (neaps ebb) to 2.8 km/h (springs ebb). Although the river receives some sewage discharge, industrial pollution is very light, with much of the river lined by mud banks and in its natural undeveloped state. Probably the most conspicuous recent constructions have

TABLE 2

SURFACE SEAWATER TEMPERATURE AND SALINITY DATA

	LANGSTONE HARBOUR				PORTSMOUTH HARBOUR				FAIREY MARINA				SWANWICK MARINA			
	1978		1979		1978		1979		1978		1979		1978		1979	
	T°C	S ‰	T°C	S ‰	T°C	S ‰	T°C	S ‰	T°C	S ‰	T°C	S ‰	T°C	S ‰	T°C	S ‰
Jan.	5.3	32.0	2.6	33.0	6	31.0	2.5	33.0	5.5	27.0	3.6	29.0	5.0	13.0	3.0	28.0
Feb.	3.5	34.3	2.0	30.7	5.7	34.0	4.5	32.0	5.5	27.3	5.0	28.0	5.0	22.4	4.5	21.0
Mar.	6.0	32.0	4.2	32.0	5.8	33.5	5.0	32.0	6.6	25.5	5.0	29.6	6.8	22.0	5.0	25.3
Apr.	7.7	31.5	7.3	30.6	7.5	33.3	9.5	33.2	7.8	24.0	10.0	28.0	7.6	27.6	11.5	20.0
May	11.8	32.5	10.5	32.8	10.5	34.0	12.5	31.7	12.5	31.2	13.5	28.0	12.8	27.3	13.5	29.0
June	15.6	33.5	14.7	31.7	16.5	35.3	14.0	31.6	17.5	31.3	15.0	29.0	18.5	28.6	15.5	26.3
July	16.4	32.0	18.0	32.3	16.0	31.6	18.0	32.3	17.0	29.3	18.5	29.6	17.5	26.6	19.0	25.6
Aug.	17.7	32.2	17.0	34.0	18.0	32.2	18.0	34.0	19.0	29.6	19.0	32.2	19.0	25.6	19.0	31.3
Sept.	16.5	33.3	15.8	33.0	17.5	32.0	17.0	34.0	17.8	30.6	17.5	31.1	16.0	29.3	17.1	27.0
Oct.	13.3	33.0	16.0	32.5	14.0	32.5	16.0	34.0	14.0	30.0	16.0	31.3	14.0	26.2	16.0	30.0
Nov.	11.0	33.5	12.0	32.5	11.0	33.5	13.0	32.5	11.1	31.0	12.0	31.3	11.2	29.6	12.0	26.0
Dec.	6.3	30.7	4.2	33.5	6.5	32.0	11.0	33.2	7.0	26.6	11.0	28.6	7.1	16.1	11.0	20.1

N.B. Temperatures given for Langstone are monthly averages based on daily readings. All other figures are based on single monthly recordings.

been that of four large yachting marinas, the Swanwick, Mercury, Port Hamble and the Fairey, which are fairly evenly spaced out down the broader lower reaches of the river (Fig. 1 *b*). It is the buoyant «floats» used to support the pontoons of these four marinas which have been studied in the present paper. At the Mercury and Fairey Marinas the polystyrene floats were covered by fibreglass, whereas at the Port Hamble and Swanwick Marinas they were covered with metal and concrete respectively. Salinity data recorded during 1978 and 1979 (Table 2) indicates that the floating pontoons of all four marinas can be frequently immersed in waters of reduced salinity; this especially applies at the Swanwick marina where generally lower salinity levels were recorded than at the Fairey Marina. No significant differences, however, were noted in the surface water temperature at the Swanwick and Fairey Marinas; the seasonal ranges observed were similar to those recorded in the fully marine Portsmouth and Langstone Harbours.

METHODS

At each site general collections of fouling algae were initially made from the vertical sides of the floating structure present in both exposed and sheltered regions. Samples were obtained from both the upper wave washed water line area as well as the lower permanently submerged areas. At most sites, two collections were made during 1979: a winter/early spring collection in late February and a summer collection in late August.

For more detailed studies on the structure of the upper wave washed algal community present on the variously exposed vertical sides a continuous belt quadrat was used. Ten mm square samples of algae were successively removed down a vertical line transect which extended from the upper limits of algal growth down to the true water line area (determined on a very calm day). On the side of each floating structure 5 belt quadrats were taken, 10 mm apart, and for each 10 mm level above the water line, a collective assessment was made of the abundance of all recorded species (according to the scale — abundant, common, present, rare) based upon analysis of the five horizontal samples. Repli dishes 100 × 100 mmsq.) holding twenty five compartments were found useful for storage of each sample before identification was carried out.

RESULTS

(1) PORTSMOUTH HARBOUR

Altogether approximately 57 algae were recorded at the Gosport Marina, comprising 16 species of Chlorophyta, 17 species of Phaeophyta and 24 species of Rhodophyta (Table 3). In addition to a slight seasonal variation in the flora some differences were recorded in the vegetation of the exposed and sheltered floats, and are treated separately.

(a) *Exposed Floats*

Examination of the outer, more exposed, floats during February revealed a quite well developed wave washed community of predominantly green algae which extended between 100 and 220 mm above the water line. From both general collections and transect data (Fig. 3), the algal community was found to be stratified into several horizontal bands. There was an upper, sometimes quite extensive crust-like community of microscopic green algae comprised of *Chlorococcus*-like cells, occurring both singly and in colonies, along with young spore and filamentous germling stages of unknown taxonomic identity. Below this microscopic community the float surface was usually covered right down to the water line by thick growths of thalloid green algae belonging to the genera *Blidingia* and *Enteromorpha*. The transect data further revealed these algae to be zoned with *Blidingia* spp. (identified as *B. marginata* and *B. minima;* but see Parke and Dixon, 1976, page 567, note 40) dominating the upper regions and *Enteromorpha prolifera* and *Enteromorpha intestinalis* jointly dominating the mid and lower regions, sometimes with *Enteromorpha linza* extending out at the water line. In general, the upper *Blidingia* dominated zone supported a very reduced underflora, comprised very largely of microscopic green algae, unicellular diatoms, blue-green algae and some chrysophyte algae, although localised patches of the two filamentous green algae

TABLE 3

DISTRIBUTION OF MARINE FOULING ALGAE ON FLOATING STRUCTURES IN THE SOLENT *

	Ports. Harbour		Lang. Rafts		Fairey		Pt. Hamble		Mercury		Swanwick	
	Feb	*Aug*	*Feb*	*Aug*	*Feb*	*Aug*	*Feb*	*Aug*	*Feb*	*Aug*	*Feb*	*Aug*
Chlorophyta:												
Blidingia spp	+	+	+	+	+	+	+		+		+	+
Bryopsis plumosa	+	+	+	+	+	+	+		+		+	
Chaetomorpha linum	+	+	+	+		+					+	
Cladophora sp	+	+	+	+	+	+	+		+		+	+
Codium fragile var. tometosoides	+	+	+	+			+					
Derbesia marina	+	+			+		+					
Enteromorpha flexuosa	+	+	+				+					
Enteromorpha intestinalis	+			+	+	+	+		+		+	
Enteromorpha linza	+	+	+	+			+		+			
Enteromorpha prolifera	+		+	+	+	+	+		+		+	+
Percursaria percursa	+	+		+								
Rhizoclonium riparium	+	+	+	+			+				+	
Ulothrix flacca	+	+	+	+	+	+	+		+		+	+
Ulothrix pseudoflacca	+	+	+	+	+	+	+		+		+	+
Ulothrix subflaccida									+			
Ulva lactuca	+	+	+	+	+	+	+		+		+	+
Urospora penicilliformis	+		+	+	+		+		+			
NUMBER OF SPECIES	16		14		11		11		11		10	

TABLE 3 (Continued.)

Phaeophyta:												
Acinetospora crinita		+		+		+	+					
Cutleria multifida		+										
Desmarestia viridis	+		+		+							
Dictyota dichotoma	+	+										
Ectocarpus fasciculatus	+	+	+									
Ectocarpus siliculosus	+	+	+	+	+	+	+		+		+	+
Fucus spiralis			+	+					+			
Fucus vesiculosus			+	+								
Fucus sp. (young plants) ...			+		+		+		+		+	
Giffordia granulosa	+	+	+	+	+	+	+		+		+	
Giffordia hincksiae	+		+									
Giffordia sandriana	+		+									
Giffordia sp		+		+								
Hecatonema maculans				+								
Laminaria digitata	+	+										
Laminaria saccharina	+	+	+	+	+	+	+					
Myrionema strangulans	+	+	+	+								
Petalonia fascia	+		+	+	+		+		+		+	
Petalonia zosterifolia			+	+								
Petroderma maculiforme ...				+								
Pilayella littoralis	+		+	+	+		+		+			
Sargassum muticum	+	+	+	+	+	+						
Scytosiphon lomentaria	+		+	+					+			
Sphacelaria sp			+	+								
NUMBER OF SPECIES ...	17		21		9		7		7		4	

TABLE 3 (Continued.)

Rhodophyta:												
Antithamnion plumula ……	+				+							
Audouniella sp ……………	+	+	+	+	+	+	+		+			
Bangia atropurpurea ………	+	+	+	+								
Callithamnion hookeri ……	+								+		+	
Callithamnion roseum ……	+				+				+		+	
Callithamnion tetragonum.	+	+	+	+	+	+	+					
Callophyllis laciniata …….	+	+	+	+	+	+						
Ceramium diaphanum ……					+		+		+		+	
Ceramium rubrum ……….	+	+	+	+	+	+	+		+			
Chondrus crispus …………	+	+	+	+	+	+	+		+		+	+
Chylocladia verticillata ……			+									
Cryptopleura ramosum ……	+	+	+	+	+	+	+					
Cystoclonium purpureum …	+	+	+	+								
Goniotrichum alsidii ………	+	+	+	+								
Grateloupia doryphora ……	+	+	+	+								
Gracilaria verrucosa ………	+	+	+	+	+	+	+					
Griffithsia corallinoides …	+	+	+	+								
Griffithsia flosculosa …….	+	+	+	+								
Lomentaria clavellosa ……	+		+									
Nitophyllum punctatum …	+	+	+	+								
Polysiphonia brodiaei ……	+	+	+	+								
Polysiphonia elongata ……	+		+		+		+		+		+	
Polysiphonia nigrescens …	+	+	+	+	+	+	+		+		+	+
Polysiphonia urceolata ……	+	+	+	+	+	+	+		+		+	+
Polysiphonia sp ……………	+	+	+	+		+	+		+		+	+
Porphyra umbilicalis ………			+	+								
Porphyra sp ………………	+	+			+						+	
Porphyridium purpureum …			+	+	+	+			+			
NUMBER OF SPECIES …	24		23		16		11		11		9	
TOTAL NUMBER OF SPECIES.	57		58		36		32		29		23	

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* Taxonomic nomenclature follows that of Parke and Dixon 1976.

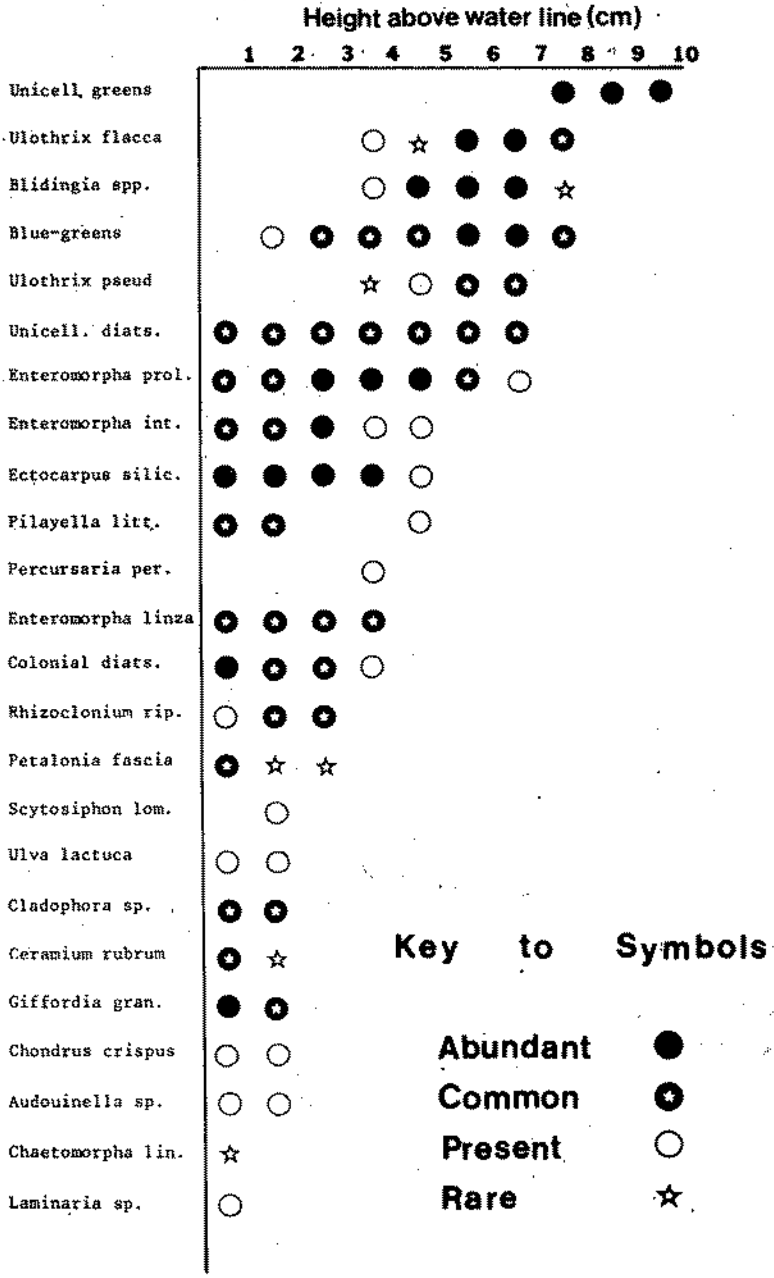

FIG. 3.—Portsmouth Harbour. Vertical distribution of marine algae. February. Outer Region.

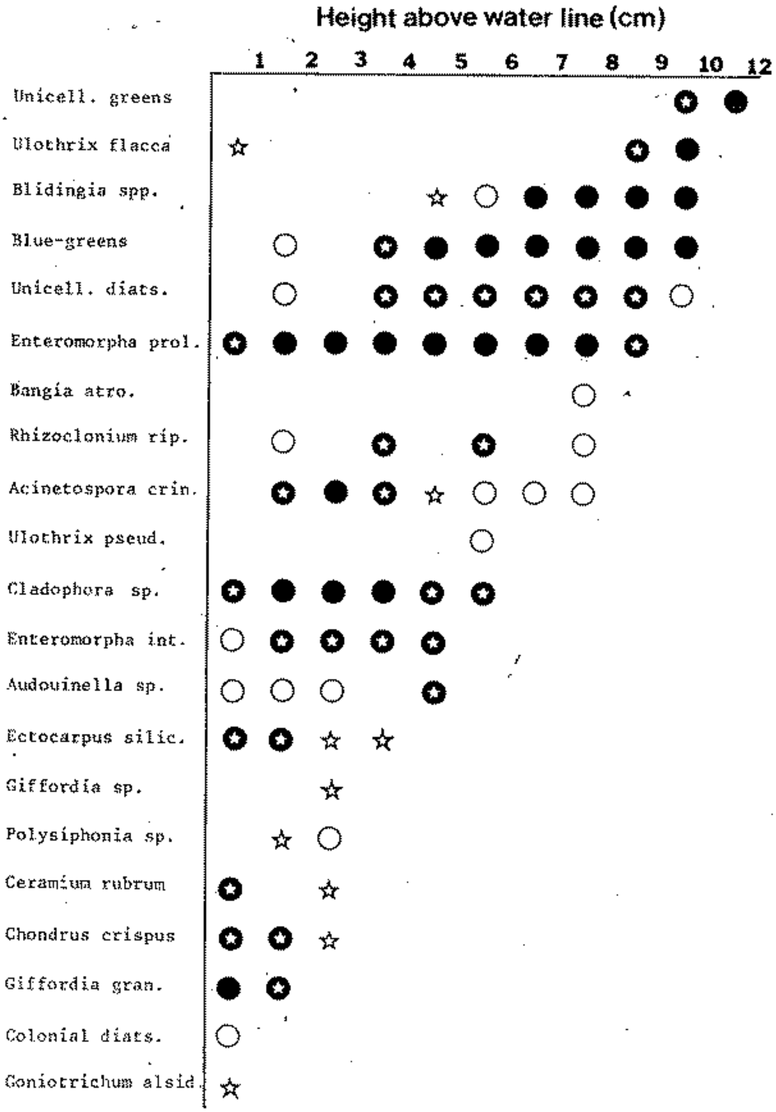

FIG. 4.—Portsmouth Harbour. Vertical distribution of marine algae. August. Outer Region.

Ulothrix flacca and *Ulothrix pseudoflacca* and the red alga *Bengia atropurpurea* were also observed.

In addition to unicellular diatoms and blue-green algae a wide range of macroscopic algal species were identified in the undervegetation of the *Enteromorpha* spp. In the upper regions these commonly included green algae such as *Blidingia* and *Ulothrix* spp. and occasionally *Percursaria percursa* whilst in the mid and lower regions, small tufts of colonial diatoms and various brown algae such as *Ectocarpus siliculosus* and less commonly *Giffordia sandriana*, *Petalonia fascia*, *Scytosiphon lomenta-*

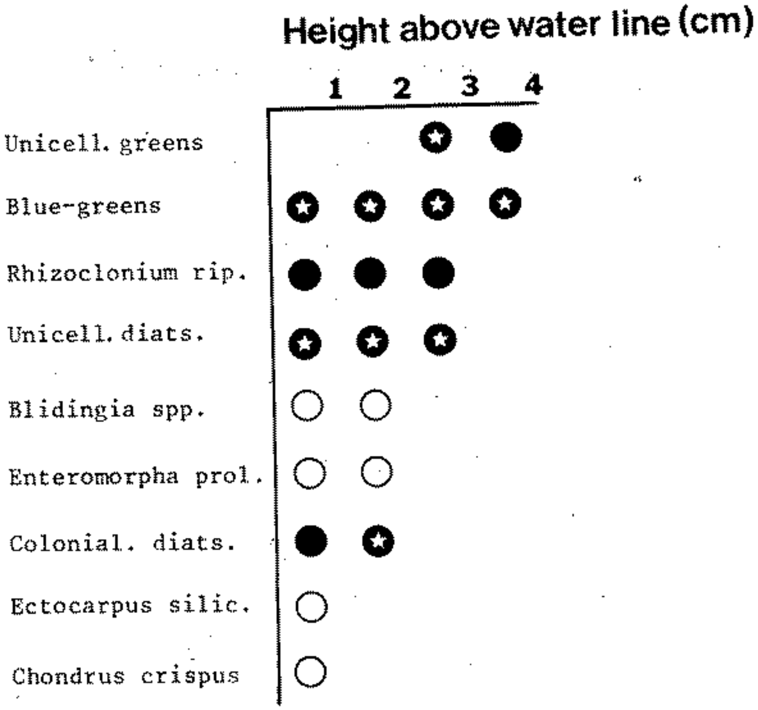

FIG. 5.—Portsmouth Harbour. Vertical distribution of marine algae. February. Inner Region. Transect 1.

ria and *Pilayella littoralis* were present. At the water line *Ectocarpus siliculosus* and colonial diatoms were usually the principal contributors to the underflora, although very often the brown ectocarpoid alga *Giffordia granulosa* was also very common. Additional green algae associated with the water line area included in particular *Ulva lactuca,* and various amounts of *Cladophora* sp., *Rhizoclonium riparium, Ulva lactuca* and *Chaetomorpha linum.* A particularly characteristic feature of the water line region was the occurrence of tufts of red algae, the most common species present being *Grateloupia doryphora, Ceramium rubrum, Chondrus crispus, Callithamnion tetragonium* and varios *Polysiphonia* spp. Occasionally small young blades belonging to the large brown algal genus *Laminaria* also appeared in the water line area samples.

The principal algal colonisers of the float sides below the water line, in the permanently submerged region, were the two laminarians, *Laminaria digitata* and *Laminaria saccharina.* The former species, *Laminaria digitata,* was more prevalent on the sides of the outer exposed and constantly buffeted floats, whilst *Laminaria saccharina,* although not uncommonly associated with it, dominated the slightly more sheltered float sides along with occasional *Sargassum muticum.* Although both these species periodically supported an extensive epiphytic flora on their blade tips including species such as *Ectocarpus fasciculatus, Giffordia granulosa, Giffordia hincksiaei* and *Callithamnion tetragonum,* usually a much reduced undervegetation was observed attached to the float sides. Algae such as *Callithamnion tetragonum, Ceramium rubrum* and *Chondrus crispus* were not uncommon just below the water line along with some *Gracilaria verrucosa, Grateloupia doryphora* and *Ulva lactuca.* Slightly further down and more sporadic in their occurrence could be found plants of *Griffithsia flosculosa, Polysiphonia elongata* and *Polysiphonia nigrescens.* The most extensive colonisers of the float sides in the

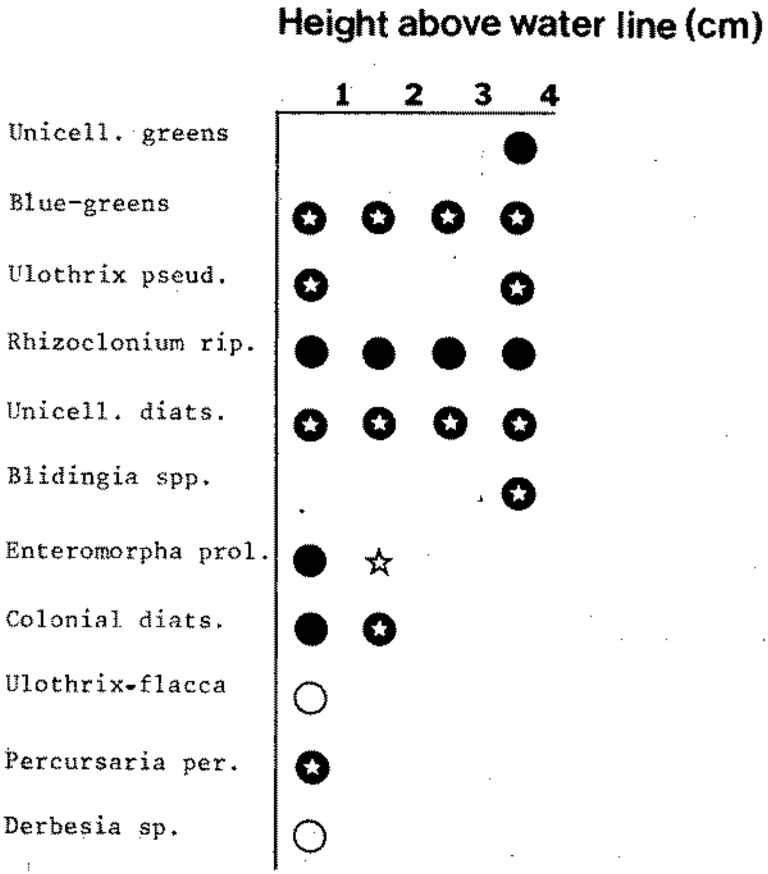

FIG. 6.—Portsmouth Harbour. Vertical distribution of marine algae. February. Inner Region. Transect 2.

submerged regions, however, were fouling animals, in particular species of barnacles and tube worms.

Comparative studies on the outer float sides during the August sampling period (see Figure 4) revealed very few changes in the overall floristic composition and zonation pattern. As previously described there was an upper microscopic community of predominantly green algae, a slightly lower community dominated by *Blidingia* spp. and a broad mid to lower region community comprised of *Enteromorpha* spp., principally *Enteromorpha intestinalis* and *Enteromorpha prolifera*. The composition and structure of the undervegetation also remained very similar to that recorded in February and included unicellular diatoms, blue-green algae, *Blidingia* spp., *Cladophora* sp., *Ectocarpus siliculosus, Rhizoclonium riparium* and *Ulothrix* spp. Red algae, such as *Ceramium rubrum, Chondrus crispus* and *Polysiphonia* spp. remained a prominent feature of the water line area along with green algae such as *Cladophora* sp. and *Ulva lactuca* and the brown alga *Giffordia granulosa*. However, some noteworthy features of the wave washed float regions during August only, included a reduction in the growth or occurrence of the *Ulothrix* dominated uuper filamentous green algal community, as well as a number of brown algae, in particular, *Petalonia fascia* and *Scytosiphon lomentaria,* and to a much lesser extent *Ectocarpus siliculosus* and *Pilayella littoralis* along with colonial diatoms and the green thalloid alga *Enteromorpha linza.* Growth of the two algae *Cladophora* sp. and

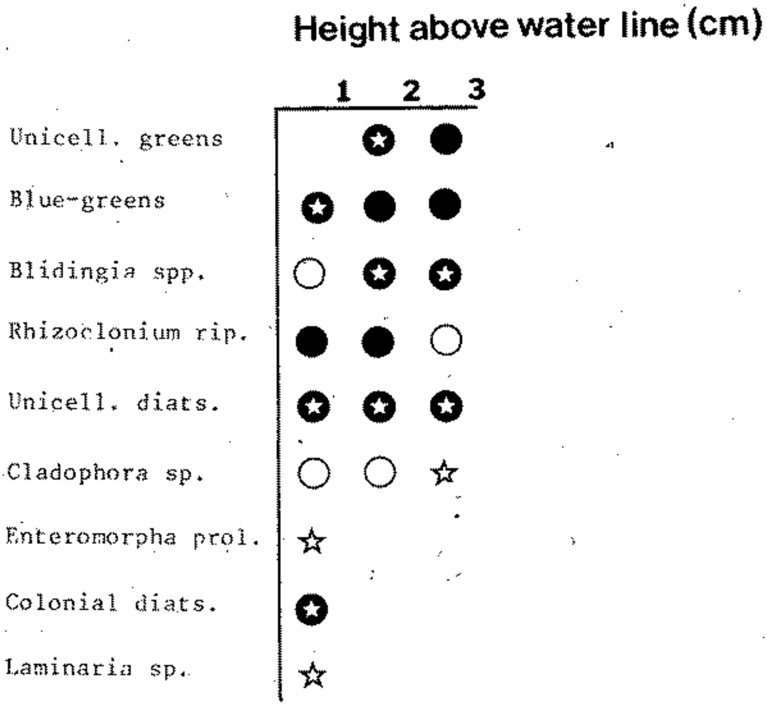

FIG. 7.—Portsmouth Harbour. Vertical distribution of marine algae. February. Inner Region. Transect 3.

Acinetospora crinita, on the other hand, was more noticeably enhanced during the summer period.

(b) *Sheltered Floats*

In comparison to the outer floats, only a small wave washed green algal community, rarely exceeding 30-40 mm in height, was observed on the sides of the inner sheltered floats during February (Figs. 5-7). Below the upper small crust-like community of microscopic green algae the wave washed sides were usually covered down to the water line by *Blidingia* spp. and/or fluffy growths of *Rhizoclonium riparium,* with an underflora largely comprised of unicellular diatoms, blue-green algae and some *Ulothrix pseudoflacca.* No distinct *Enteromorpha* dominated zone was evident on the sides of these sheltered floats; however, usually *Enteromorpha prolifera* occurred intermixed with the *Blidingia* spp. in the lower regions and was not uncommon at the water line, where it was associated with algae such as *Chaetomorpha linum, Chondrus crispus, Cladophora* sp., *Derbesia marina, Ectocarpus siliculosus,* young *Laminaria* sp., *Percusaria percursa, Pilayella littoralis* and abundant colonial diatoms. Below the water line, various fouling animals, in particular tube worms and barnacles with large, scattered, slipper limpets (*Crepidula fornicata*) covered the surface of the floats with the algae generally occurring as a low sward of secondary fouling organisms. The most abundant algae recorded were *Derbesia marina, Cladophora* sp. and colonial diatoms, along with varying amounts of green algae such as *Bryopsis plumosa, Enteromorpha prolifera, Rhizoclonium riparium,* brown algae such as *Giffordia granulosa* and red algae such as *Antithamnion plumula, Ceramium rubrum, Griffithsia corallinoides, Nitophyllum punctatum, Polysiphonia urceolata and Polysiphonia* sp. Macroscopic algae more infrequently present, included *Codium fragile* var. *tomentosoides, Laminaria sac-*

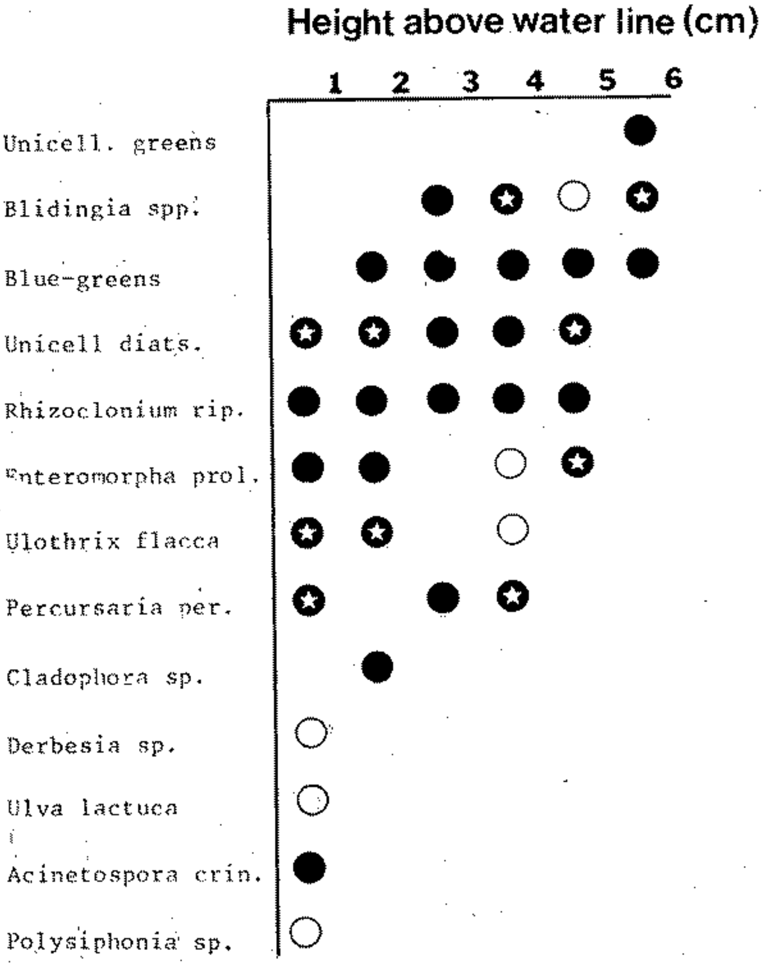

FIG. 8.—Portsmouth Harbour. Vertical distribution of marine algae. August. Inner Region. Transect 1.

charina, Polysiphonia nigrescens and more rarely *Gracilaria verrucosa* and *Laminaria digitata*.

Examination of the wave washed community in August (Figs. 8-10) revealed only minor changes in the structure of the fouling vegetation, with microscopic green algae occupying the higher levels and *Blidingia* spp., *Enteromorpha prolifera* and *Rhizoclonium riparium* maintaining their dominance over the greater part of the surface with an undervegetation largely comprised of unicellular diatoms, blue-green algae, *Ulothrix* spp. and *Percursaria percursa*. Except for a notable influx of the brown ectocarpoid alga *Acinetospora crinita*, the floristic composition of the water line region (and the permanently submerged region) remained very similar to that recorded in February. However, a number of algae appeared to be more abundant including *Cladophora* sp., *Derbesia marina* and *Rhizoclonium riparium* and to a lesser extent, *Chaetomorpha linum* and *Ulva lactuca*. Colonial diatoms, on the other hand, were markedly reduced in growth.

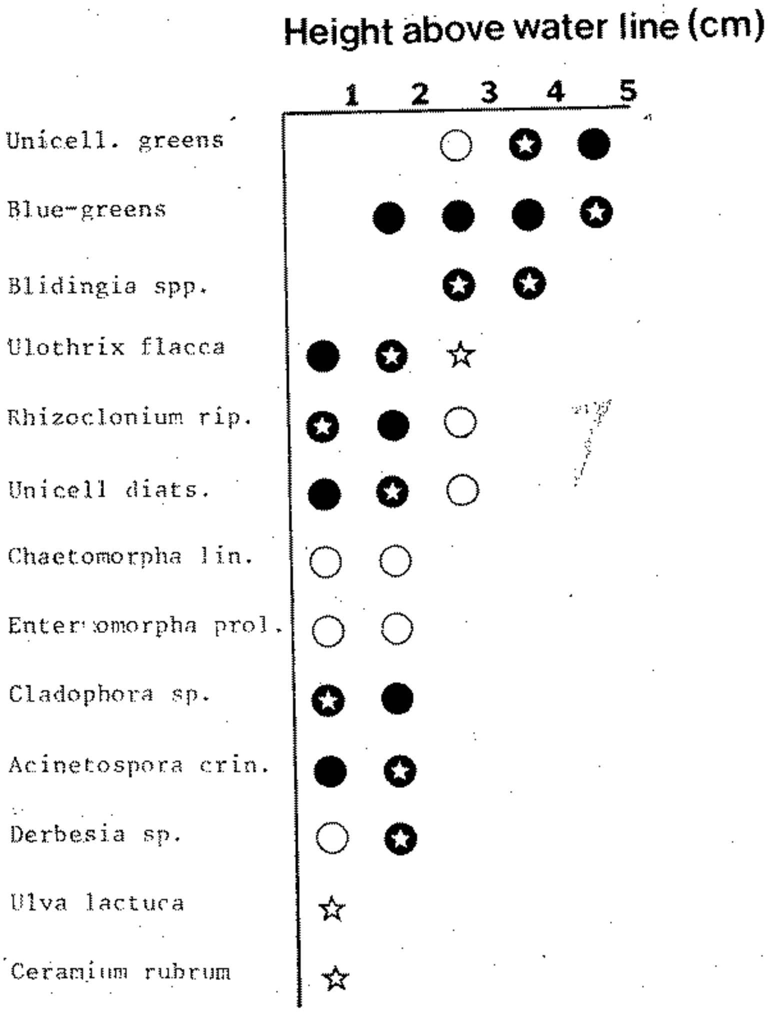

FIG. 9.—Portsmouth Harbour. Vertical distribution of marine algae. August. Inner Region. Transect 2.

(2) LANGSTONE HARBOUR

Altogether approximately 58 algae were recorded on the sides of the Langstone Rafts, comprising 14 species of Chlorophyta, 21 species of Phaeophyta and 23 species of Rhodophyta (Table 3). The flora of the three regions examined are treated separately.

(a) *Inner sheltered walls*

Examination of the very sheltered, inner walls of the rafts during February revealed a very reduced wave washed community of green algae, extending 40-50 mm above the water line (Figs. 11-13). Unicellular green algae, identical to those recorded in Gosport Harbour occupied the upper regions of the community, usually in association with *Ulothrix flacca* and *Ulothrix pseudoflacca*. Both the above *Ulothrix* spp. also commonly extended down towards the water line although in both the mid and lower regions of the wave washed community they generally became subordinate to thalli of *Blidingia* spp. and *Enteromorpha prolifera*/*E. intestinalis* respectively, along with

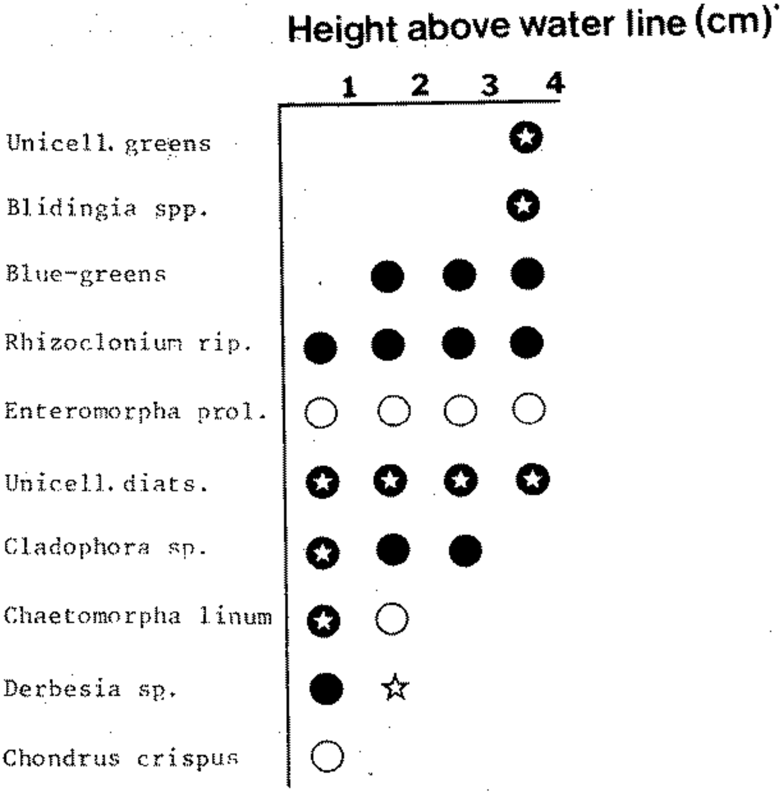

FIG. 10.—Portsmouth Harbour. Vertical distribution of marine algae. August. Inner Region. Transect 3.

an associated underflora of unicellular diatoms, colonial diatoms, blue-green algae and *Cladophora* sp. Both colonial diatoms and *Cladophora* sp. were also recorded in great abundance in the water line region with additional algae such as *Rhizoclonium riparium, Polysiphonia* sp. young *Laminaria* sp., *Sphacelaria* sp. and *Ulva lactuca*. One particularly interesting feature of the wave washed community was the common occurrence of the usually rare unicellular red alga *Porphyrideum purpureum*.

Below the water line the walls were very largely covered by fouling animals, in particular tube dwelling amphipods, barnacles, tube worms, hydroids, erect and encrusting tunicates sponges and more rarely anemones. Although colonial diatoms were widespread and abundant secondary foulers on the animals; in general algal growths were more confined to the upper water line region and occurred only sporadically. Brown algae recorded included *Desmarestia viridis,* and the large species *Laminaria saccharina* and *Sargassum muticum;* green algae included *Bryopsis plumosa, Codium fragile* var. *tomentosoides* and *Ulva lactuca;* whilst red algae included *Ceramium rubrum, Griffithsia flosculosa, Nitophyllum punctatum* and *Polysiphonia nigrescens.*

Comparative studies on the float sides during August (Figs. 14-16) revealed only minor differences in the algal community, with *Blidingia* spp., *Enteromorpha* spp. (*E. intestinalis, E. prolifera*) and to a lesser extent *Rhizolonium riparium* still dominating the wave washed regions just below the upper microscopic green algal community. Amongst the smaller algae recorded, especially those present in the undervegetation, some notable changes included a reduction in the growth of *Ulothrix* spp. co-

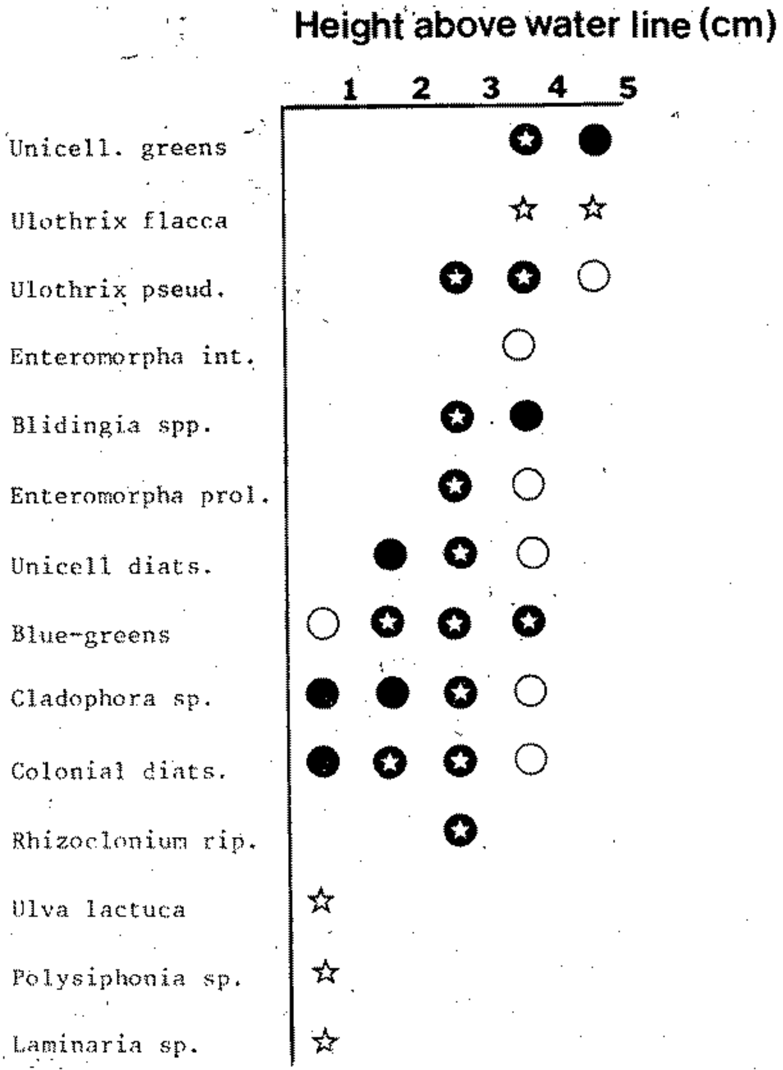

FIG. 11.—Langstone Harbour. Vertical distribution of marine algae. February. Inner sheltered walls. Transect 1.

lonial diatoms and *Porphyrideum purpureum.* Growth of some algae, on the other hand, appeared to be enhanced during August; these included, in particular *Cladophora* sp. and *Rhizoclonium riparium,* and to a lesser extent, *Acinetospora crinita, Chaetomorpha linum, Ectocarpus siliculosus, Giffordia* sp. and *Polysiphonia urceolata.*

(b) *Outer exposed mid walls*

A much more prominent wave washed algal community was observed in February on the outer mid region walls of the rafts (Fig. 17). This extended, on average, up to 160 (—190) mm above the water line and was frequently recorded much higher in regions

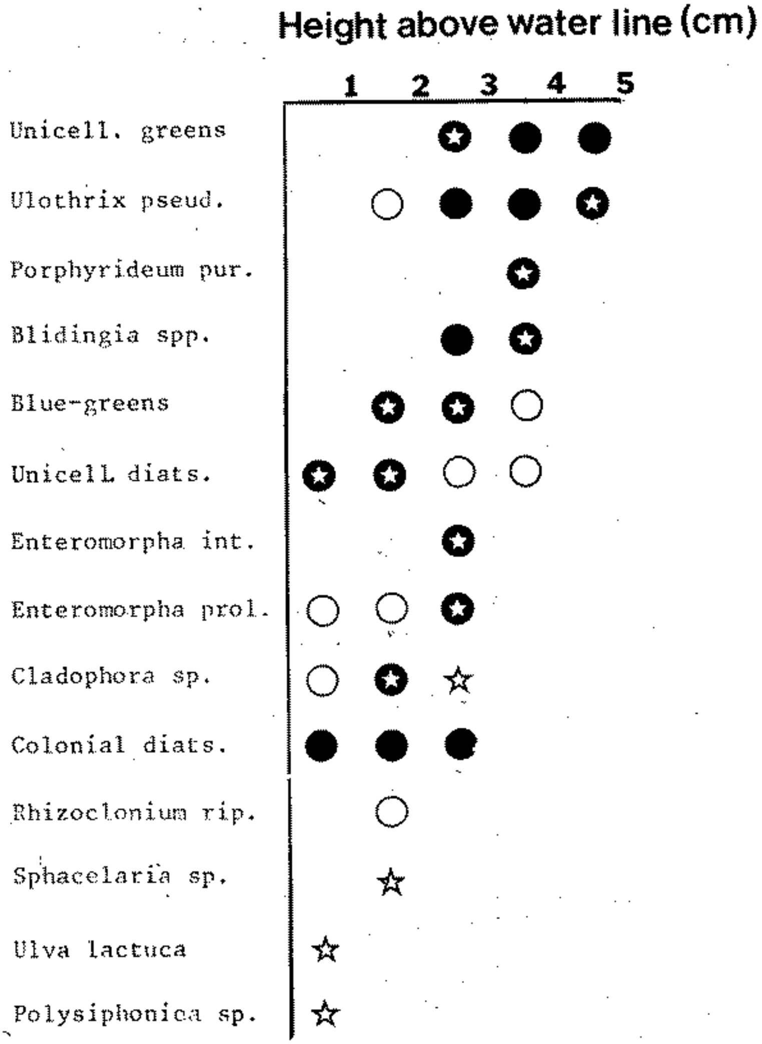

FIG. 12.—Langstone Harbour. Vertical distribution of marine algae. February. Inner sheltered walls. Transect 2.

where paint loss had occurred. In keeping with the previous studies, the community was largely dominated by green algae and a number of distinct horizontal belts or associations of algae were distinguished. The uppermost belt consisted of unicellular green algae which subsequently gave way below to a silky community of filamentous green algae, largely comprised of the three species *Urospora penicilliformis, Ulothrix flacca* and *Ulothrix pseudoflacca* and often with associated patches of the red alga *Bangia atropurpurea* present. Although quite extensively distributed down the sides of the raft wall these filamentous algae were mainly contributors to the undervegetation of an extensive mid to lower region community of thalloid green algae comprised of the two genera *Blidingia* and *Enteromorpha.* The light green thalli of the *Blidingia* spp. were quite prominent in the mid to upper regions of the wave washed community and supported an underflora largely comprised of filamentous green algae, *Bangia atropurpurea,* blue green algae and in the lower regions, uni-

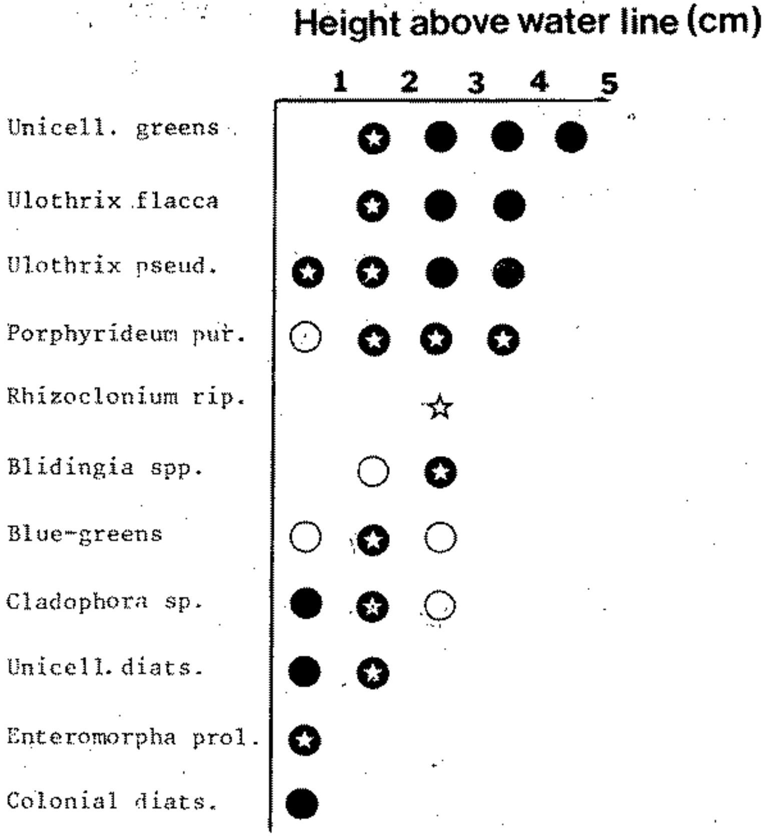

FIG. 13.—Langstone Harbour. Vertical distribution of marine algae. February. Inner sheltered walls. Transect 3.

cellular diatoms. The genus *Enteromorpha*, on the other hand, extended from the mid to lower regions of the community with *Enteromorpha prolifera* and *Enteromorpha intestinalis* occurring as a belt immediately below the *Blidingia* spp. with *Enteromorpha linza* being more prominent in the region just above the water line. A much more varied underflora was also recorded in the *Enteromorpha* belts. Algae commonly recorded under *Enteromorpha prolifera* included blue-gren algae, unicellular diatoms, colonial diatoms, *Blidingia* spp., *Ectocarpus siliculosus, Petalonia zosterifolia, Pilayella littoralis, Ulothrix flacca, Ulothrix pseudoflacca* and *Urospora penicilliformis*. Thalli of *Ectocarpus siliculosus* were particularly abundant, and frequently co-dominant with *Enteromorpha linza* in the region just above the water line, forming a brown coloured belt. A much greater variety of algae were also present along the water line region, and included not only green algae such as *Chaetomorpha linum, Cladophora* sp. and *Ulva lactuca* and brown algae such as *Ectocarpus siliculosus, Giffordia granulosa, Petalonia fascia, Petalonia zosterifolia* and *Scytosiphon lomentaria* but also more characteristically several red algae, in particular *Callithamnion tetragonum, Ceramium rubrum, Chondrus crispus, Grateloupia doryphora, Polysiphonia brodiaei, Polysiphonia nigrescens* and *Polysiphonia urceolata*.

Re-examination of the outer mid walls in August (Fig. 18) revealed that only a few changes had occurred in the composition of the algal community. These included, more

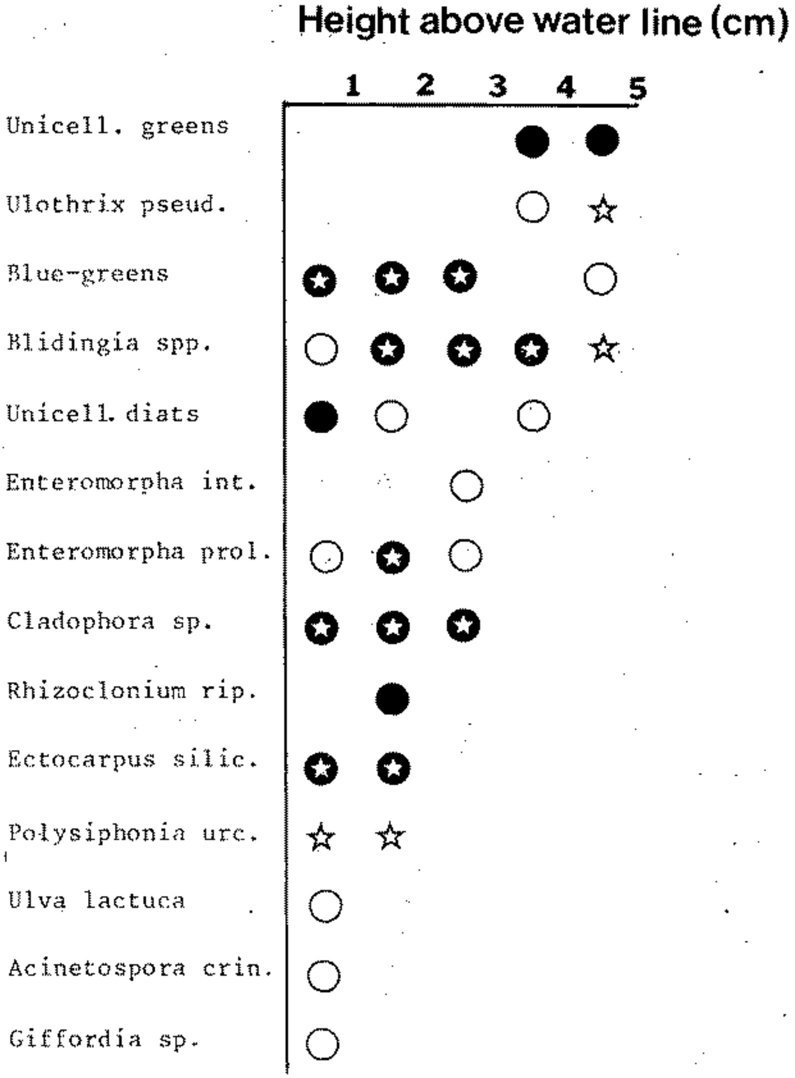

FIG. 14.—Langstone Harbour. Vertical distribution of marine algae. August. Inner sheltered walls. Transect 1.

noticeably, a reduction in the prominence of the upper filamentous green algal zone, with only *Ulothrix flacca* still commonly present as well as a more limited occurrence of algae such as *Bangia atropurpurea*, *Petalonia zosterifolia* and colonial diatoms; and to a lesser extent *Petalonia fascia* and *Ulva lactuca*.

(c) *Outer very exposed bow walls*

Although a much more extensive wave washed community was observed at the bow end during February, reaching over 400 mm in height, the floral composition and vertical stratification were almost identical to that recorded at this period for the mid regions (Fig. 19). There was an uppermost unicellular green algal community below which occurred an extensive silky community of the filamentous green algae *Ulothrix flacca*, *Ulothrix pseudoflacca* and *Urospora penicilliformis* which extended almost right down to the water line.

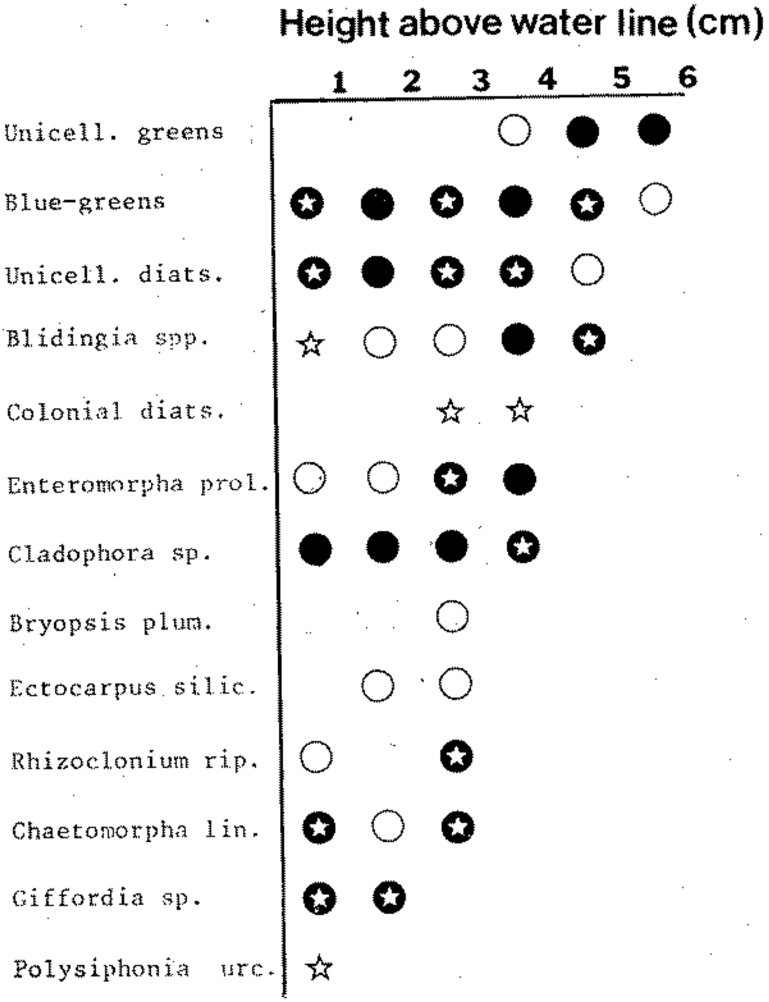

FIG. 15.—Langstone Harbour. Vertical distribution of marine algae. August. Inner sheltered walls. Transect 2.

Except for a small area at the top, however, the upper half of this community contributed to the undervegetation of an extensive *Blidingia* dominated zone whilst the lower half formed part of the undervegetation of an *Enteromorpha* dominated zone. Additional algae associated with the upper *Blidingia/Ulothrix/Urospora* community included the red algae *Bangia atropurpurea* and *Porphyra umbilicalis* as well as the more microscopic blue-green algae and unicellular green algae. The filamentous green algae were generally less abundant in the undervegetation of the two tiered *Enteromorpha* dominated community (upper *Enteromorpha prolifera*, lower *Enteromorpha linza*) and this consisted predominantly of unicellular diatoms, colonial diatoms, *Ectocarpus siliculosus* and *Petalonia zosterifolia* with variable amounts of *Petalonia fascia, Pilayella littoralis, Scytosiphon lomentaria* and *Ulva lactuca.* Some additional algae to the above, which were more restricted to the water line area were the brown alga *Giffordia granulosa,* which could be quite abundant, and a variety

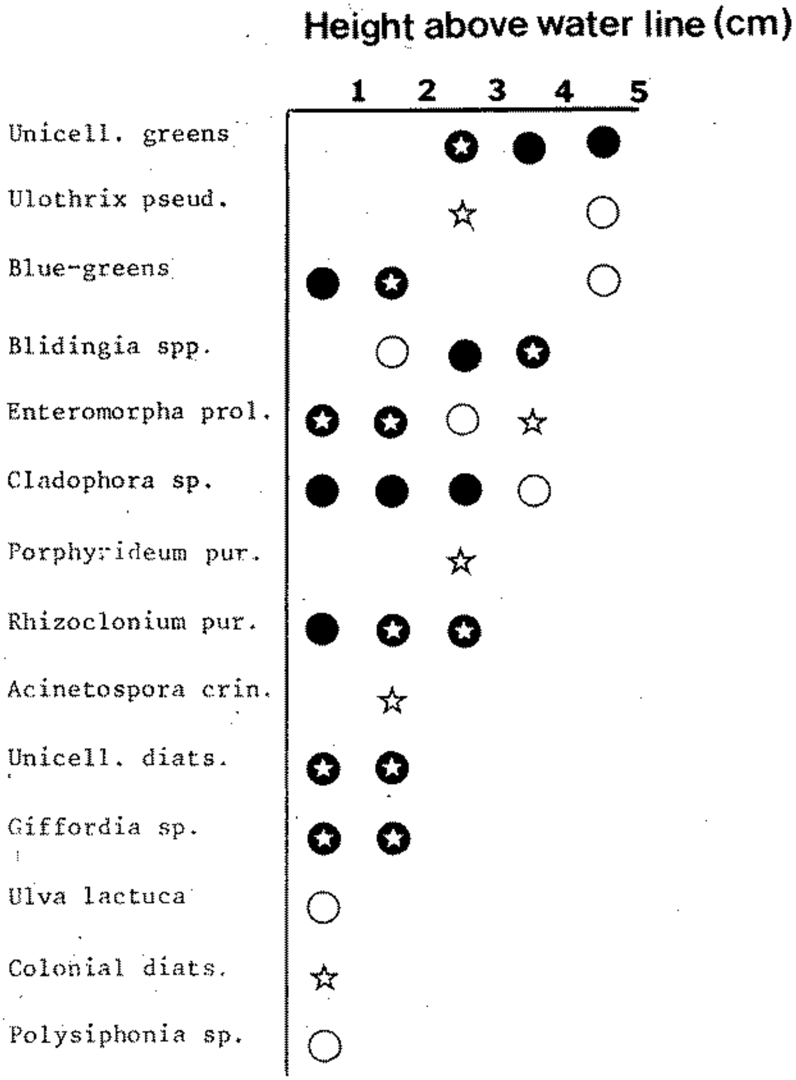

FIG. 16.—Langstone Harbour. Vertical distribution of marine algae. August. Inner sheltered walls. Transect 3.

of red algae, in particular *Callithamnium tetragonum*, *Ceramium rubrum* and *Chondrus crispus*.

A very similar algal zonation pattern and association of species was observed on the wave washed bow regions during August (Figure 20). A notable change, however, was the reduction in the extent and abundance of the filamentous green algae *Ulothrix* and *Urospora;* no distinct upper belt was observed and growths usually remained subordinate to the very extensive *Blidingia* community. Other changes, which were mainly confined to the lower regions, included reductions in the growth of colonial diatoms, unicellular diatoms, *Enteromorpha linza, Petalonia fascia, Petalonia zosterifolia* and *Ulva lactuca*.

The fouling community present below the water line at both the outer exposed sites investigated was identical and largely made up

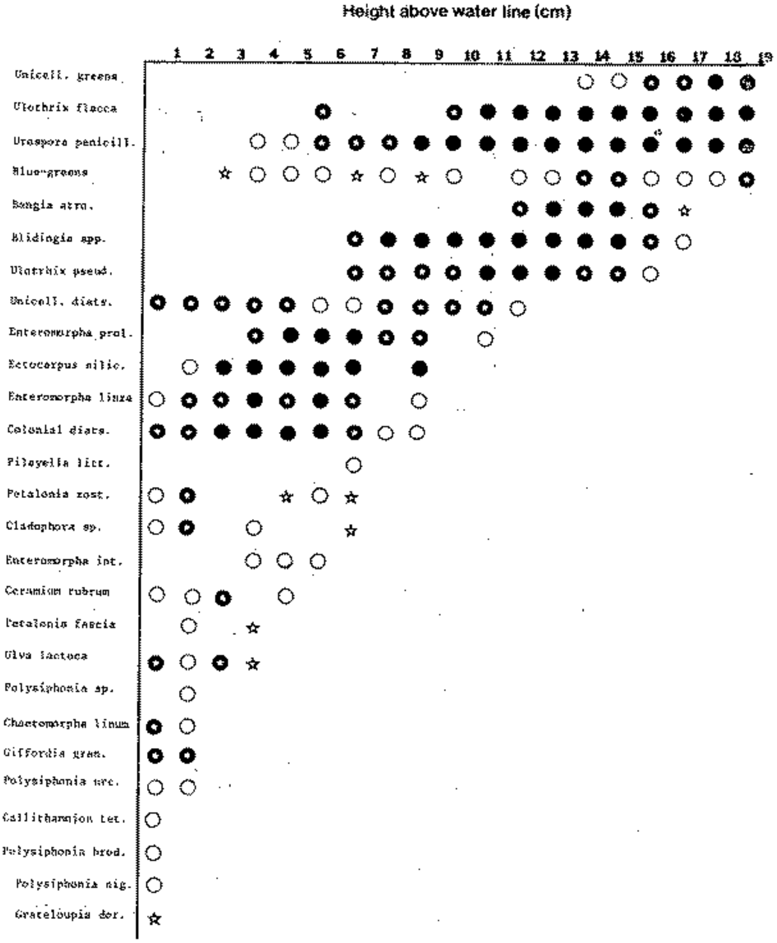

FIG. 17.—Langstone Harbour. Vertical distribution of marine algae. February. Outer exposed mid walls.

of animals, in particular tube dwelling amphipods, barnacles, various serpulids and tunicates. The most common alga recorded down the sides was *Laminaria saccharina,* although some red algae such as *Ceramium rubrum, Griffithsia flosculosa* and *Polysiphonia nigrescens* and the brown alga *Sargassum muticum* were also observed.

(3) RIVER HAMBLE

(a) *Fairey Marina*

In comparison with the Portsmouth and Langstone Harbour sites a much smaller total of 36 algae were recorded on the support floats at the Fairey Marina, comprising 11 green algae, 9 brown algae and 16 red algae (Table 3).

On the sides of the outer floats during February the wave washed algal community generally extended only 80-120 mm above the water line (Fig. 21). A thin crust of unicellular green algae usually formed an uppermost belt of between 20-40 mm in extent although in more roughened regions, caused by localised patches of glass fibres, a belt 80-120 mm wide was not uncommon. Below the unicellular algae the principal colonisers of the float sur-

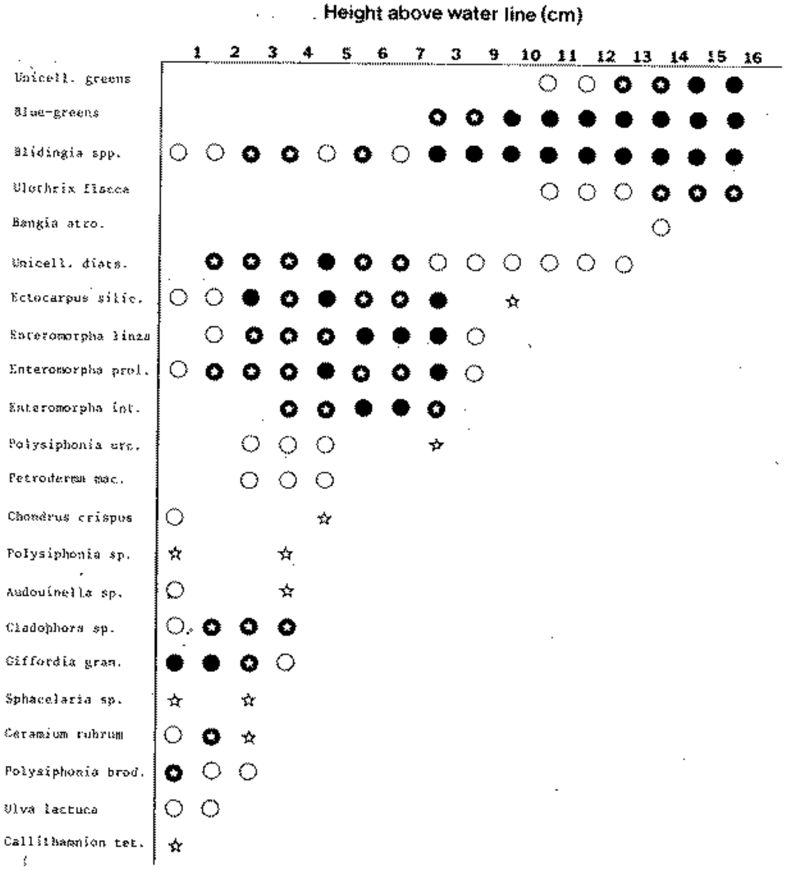

FIG. 18.—Langstone Harbour. Vertical distribution of marine algae. August. Outer exposed mid walls.

face were the two thalloid green algae *Blidingia* and *Enteromorpha*. The *Blidingia* spp. were quite widely distributed down the float sides, whilst the belt of *Enteromorpha prolifera* was more confined to the region just above the water line. Microscopic algae, such as unicellular green algae, blue-green algae and *Porphyrideum purpureum*, were mainly recorded under the *Blidingia* thalli, whereas a number of additional macroscopic algae, in particular *Cladophora* sp. colonial diatoms and *Ectocarpus siliculosus* were recorded in association with the *Enteromorpha*. Other algae found in these lower regions included blue-green algae, unicellular diatoms, *Petalonia fascia*, *Ulothrix pseudoflacca*, *Ulva lactuca* and *Urospora penicilliformis*. Some red algae, principally *Ceramium rubrum* and *Chondrus crispus* were also commonly found here.

Below the water line, the principal algae components were scattered red algae such as *Callophyllis* sp., *Ceramium rubrum*, *Chondrus crispus*, *Polysiphonia elongata* and *Polysiphonia nigrescens*, with occasional plants of *Ulva lactuca* and much more rarely, the brown algae *Desmarestia viridis*, *Laminaria saccharina* and *Sargassum muticum*. The principal animal foulers were barnacles, which occurred mainly just below the surface along with some encrusting tube worms. By contrast, very thick growths of tube worms (*Hydroides*) were found on the submerged parts of the floats in the inner more sheltered regions of the

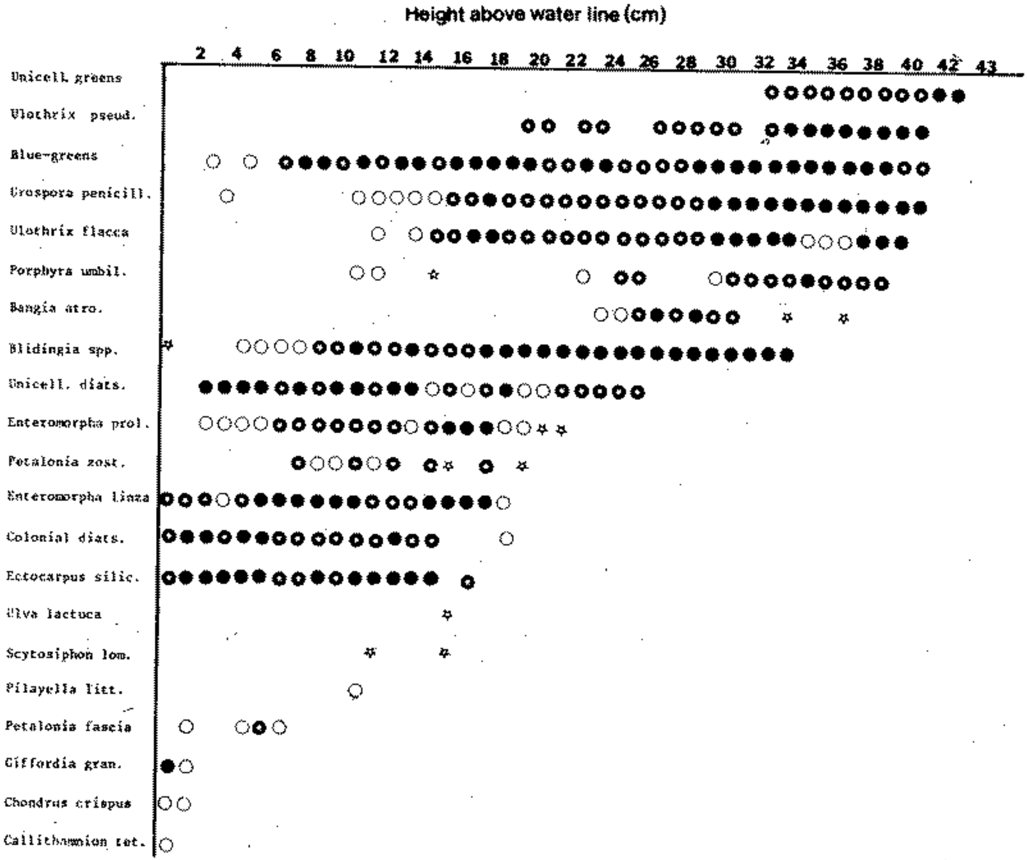

FIG. 19.—Langstone Harbour. Vertical distribution of marine algae. February. Outer very exposed bow walls.

Marina, which were often accompanied by quite large *Crepidula fornicata* and various barnacles, tube dwelling amphipods and tunicates. Numerous algae which occurred as secondary colonisers of these animals included colonial diatoms, *Callithamnion roseum*, *Ceramium rubrum*, *Chondrus crispus*, *Cladophora* sp., *Desmarestia viridis* (rare), *Nitophyllum punctatum* and *Polysiphonia nigrescens*.

Very similar algal communities to those described above were observed on the float sides during August, and only minor changes were noted in some components of the undervegetation (Fig. 22). These included reductions in the growths of colonial diatoms and, to a lesser extent *Ectocarpus siliculosus*, with an increase in the occurrence of *Cladophora* sp.

(b) *Port Hamble*

At the Port Hamble marina, 32 algae were identified, comprising 11 green algae, 7 brown algae and 11 red algae (Table 3).

On the sides of the outer pontoon floats in February the wave washed green algal community only extended up to 50-80 mm above the water line (Fig. 23). In structure it consisted of three horizontal belts of green algae, an upper belt of unicellular green algae and various Crysophytes, an intermediate belt dominated by *Blidingia* spp. and a broad lower belt dominated by *Enteromorpha* spp., principally *Enteromorpha prolifera*, with some *Enteromorpha intestinalis* and *Enteromorpha flexuosa*. Commonly associated with both the *Blidingia*

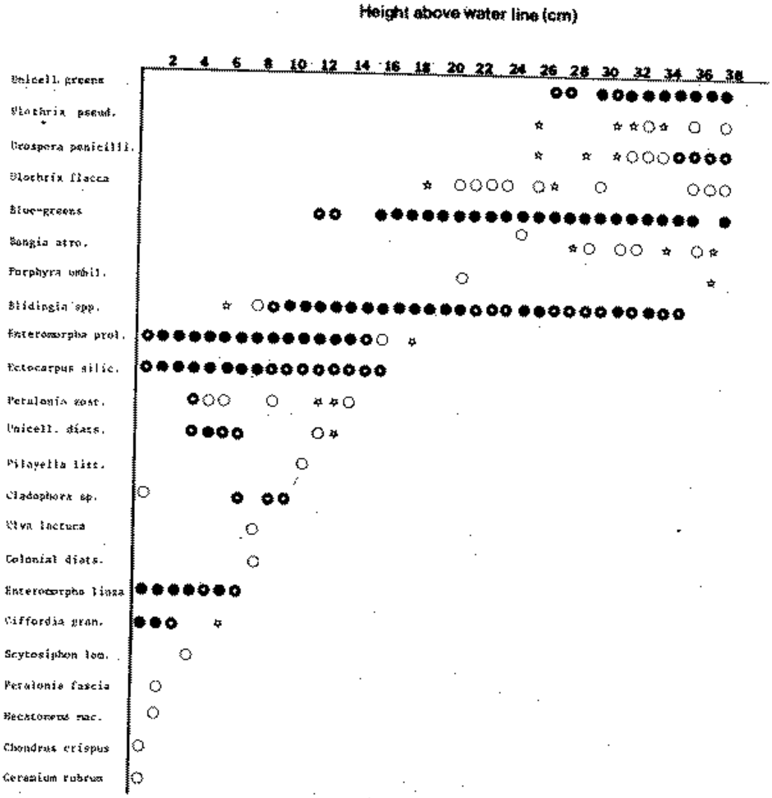

FIG. 20.—Langstone Harbour. Vertical distribution of marine algae. August. Outer very exposed bow walls.

and *Enteromorpha* spp. on the float sides were *Cladophora* sp. and *Rhizoclonium riparium* whilst growths of both colonial diatoms and *Ectocarpus siliculosus* often formed an additional distinct brown belt just above the water line. Notable additional algae recorded included *Acinetospora critina* present in the mid region and *Ceramium rubrum, Chondrus crispus, Ulothrix flacca, Ulothrix pseudoflacca* and *Ulva lactuca* present in the water line region.

Below the water line red algae were commonly recorded, including *Ceramium diaphanum, Ceramium rubrum, Chondrus crispus* and *Polysiphonia urceolata* along with colonial diatoms, occasional *Ulva lactuca* and more rarely *Laminaria saccharina*. Growths of colonial diatoms and *Derbesia marina* increased with increasing shelter.

(c) *Mercury Marina*

A total of 29 algae were recorded at the Mercury Marina, comprised of 11 green algae, 7 brown algae and 11 red algae (Table 3). In February, the wave washed algal community on the side of the outer floats extended 40-60 mm above the water line (Fig. 24), and although basically similar in structure and composition to that recorded at Port Hamble, it differed in one or two interesting features. These included (1) an association of the filamentous green algae, *Ulothrix flacca, Ulothrix pseudoflacca* and *Urospora penicilliformis* which formed silky patches amongst the *Blidingia* spp., (2) the occurrence of brown algae on the float side such as *Petalonia fascia, Pilayella littoralis* and *Scytosiphon lomentaria* and more rarely green algae such as *Chaeto-*

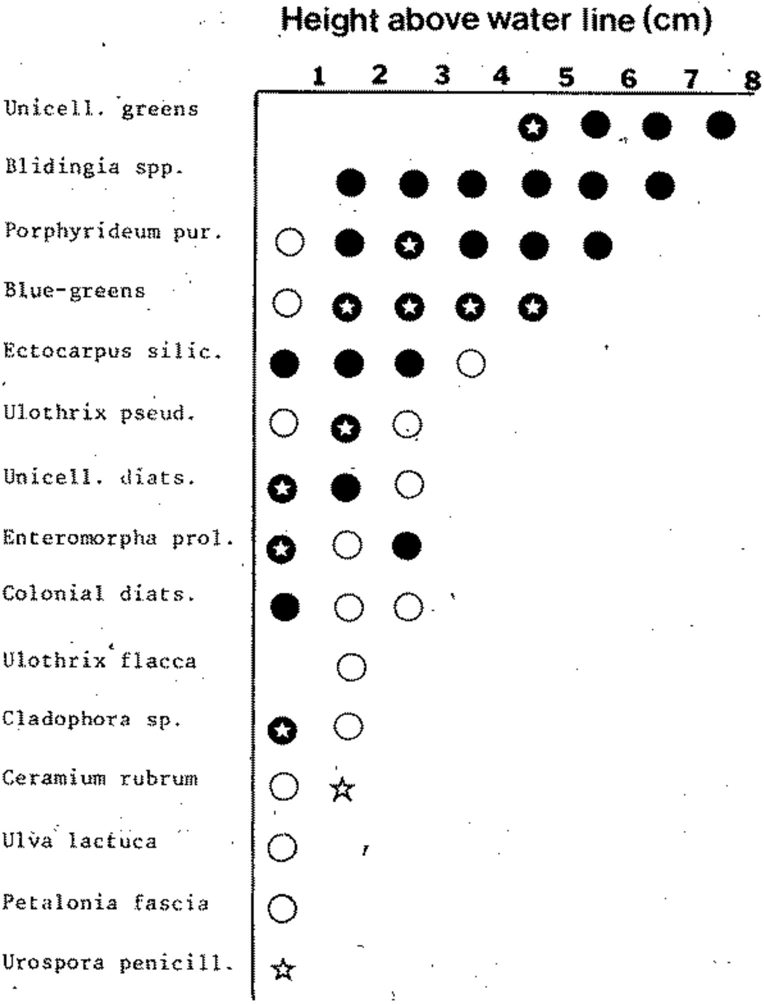

FIG. 21.—Fairey Marina. Vertical distribution of marine algae. February. Outer Region.

morpha linum and *Enteromorpha linza,* and finally (3) the presence of the brown alga *Focus spiralis* mixed with the common water line red algae *Ceramium rubrum, Chondrus crispus* and *Polysiphonia urceolata.* In addition, no *Laminaria saccharina* plants were observed in the permanently submerged regions.

In the inner, more sheltered regions, a much more reduced wave washed community was observed on the float sides, rarely exceeding 20-40 mm in height (Fig. 25). Zonation patterns were thus less frequently well defined with a mixture of algae colonising the wave washed regions; usually, however, *Blidingia* spp., with some *Ulothrix pseudoflacca* dominated the mid and upper regions, just below a unicellular green algal belt, with a mixed assemblage of algae, including colonial diatoms, unicellular diatoms, *Cladophora* sp., *Ectocarpus siliculosus, Enteromorpha prolifera, Porphyrideum purpureum* and *Polysiphonia urceolata* occupying the water line area.

Below the water line, various large red algae such as *Ceramium rubrum, Chondrus crispus,*

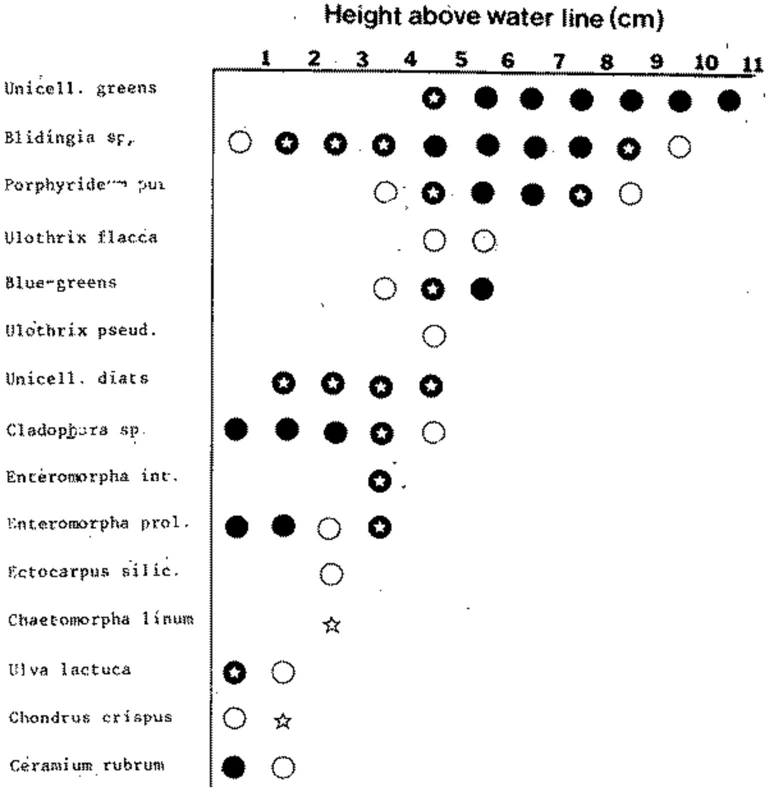

FIG. 22.—Fairey Marina. Vertical distribution of marine algae. August. Outer Region.

Polysiphonia elongata, Polysiphonia nigrescens and *Polysiphonia urceolata* were abundant down the sides of the outer floats, usually with barnacles as an underfauna. In the inner, very sheltered regions, the red algae were markedly less abundant and diverse and the sides were covered by thick growths of tube worms and barnacles which supported prolific growths of colonial diatoms.

(d) *Swanwick Marina*

A total of 23 marine algae were recorded at the Swanwick Marina, comprising 10 green algae, 4 brown algae and 9 red algae (Table 3).

In February, the wave washed community on the outer support floats extended up to 40-60 mm above the water line (Figs. 26 and 27). Below the upper unicellular green algal zone, a mixed community of the four green algae *Blidingia* spp., *Cladophora* sp., *Enteromorpha intestinalis* and *Enteromorpha prolifera* largely occurred down the sides, with an undervegetation composed of blue-green algae and unicellular diatoms. Occasionally *Blidingia* spp. formed a separate belt above the other genera. Particularly common at the water line region were *Ectocarpus siliculosus* and colonial diatoms.

Below the water line, the sides were covered mainly by thick growths of tube worms, with some barnacles and tube dwelling amphipods. The principal algal colonisers were a few red algae such as *Callithamnion roseum, Ceramium rubrum, Chondrus crispus, Polysiphonia nigrescens* and *Polysiphonia urceolata* which were largely confined to the upper regions, and abundant, more widespread colonial diatom growths.

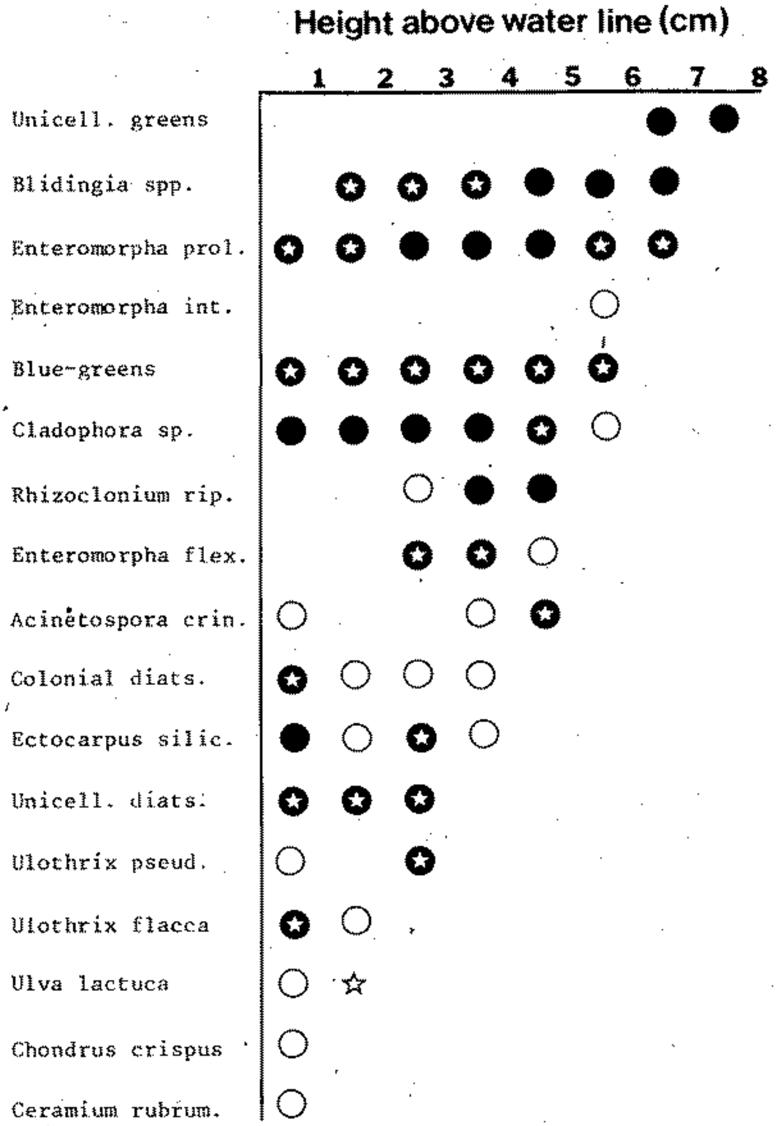

FIG. 23.—Port Hamble Marina. Vertical distribution of marine algae. February. Outer Region.

Very few seasonal changes were observed in the composition and structure of the fouling community at Swanwick (Figs. 28 and 29). Colonial diatoms, however, seemed less abundant in August, whilst growths of *Cladophora* sp., *Giffordia granulosa* and *Ulva lactuca* appeared slightly more common.

DISCUSSION

Altogether a total of 68 species of algae were recorded on the floating structures in the Solent region. These comprised 17 green algae, 23 brown algae and 28 red algae. Particularly well represented were the green algal

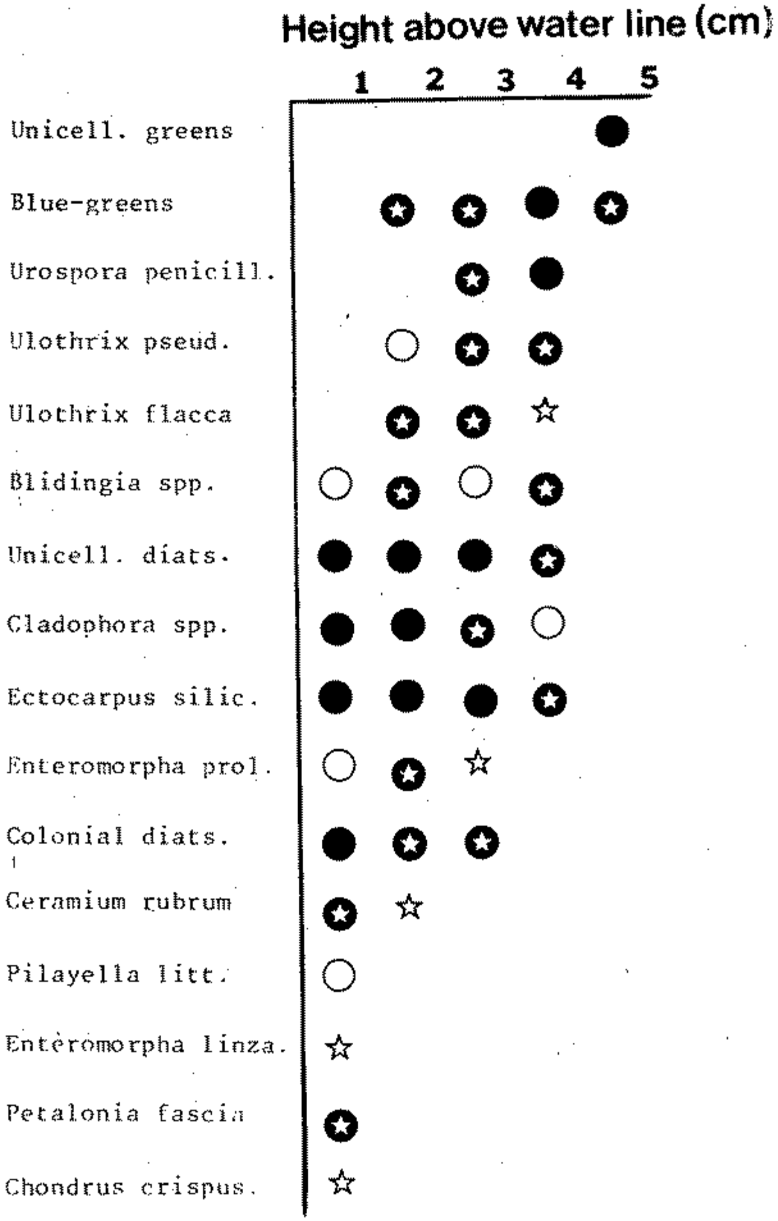

FIG. 24.—Mercury Marina. Vertical distribution of marine algae. February. Outer Region.

genera *Enteromorpha* and *Ulothrix*, the brown algal genera *Ectocarpus, Fucus, Giffordia, Laminaria* and *Petalonia* and the red algal genera *Callithamnion*, *Ceramium* and *Polysiphonia*. From an examination of Table 3 it can be seen that the most common fouling green algae recorded were *Blidingia* spp., *Cladophora* sp., *Enteromorpha intestinalis, Enteromorpha prolifera, Ulothrix flacca, Ulothrix pseudoflacca, Ulva lactuca* and *Urospora penicilliformis.* The

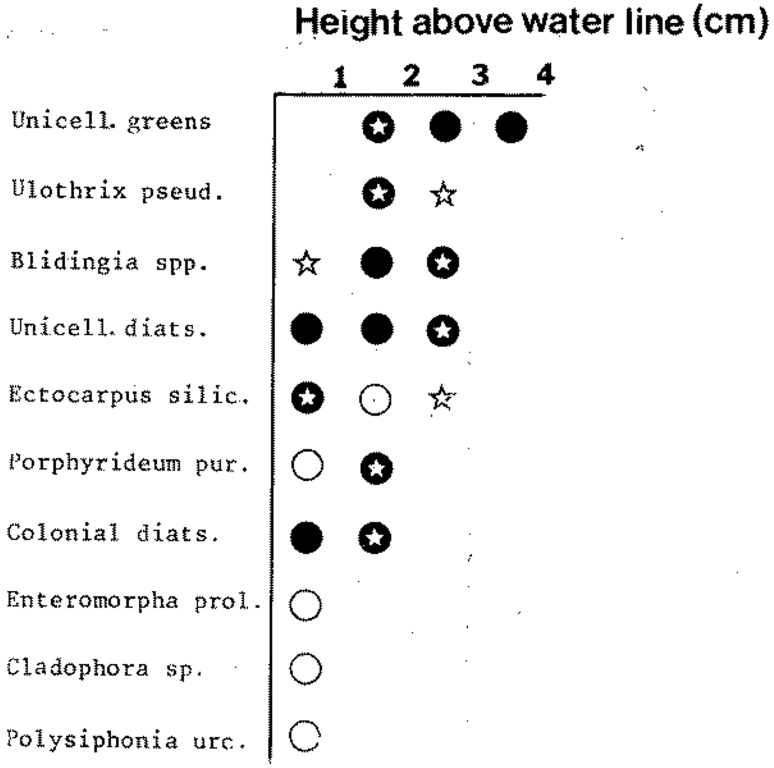

FIG. 25.—Mercury Marina. Vertical distribution of marine algae. February. Inner Region.

most common brown algae were *Ectocarpus siliculosus, Giffordia granulosa, Petalonia fascia* and *Laminaria saccharina* whilst the most common fouling red algae included *Callithamnion tetragonum, Ceramium rubrum, Chondrus crispus, Polysiphonia nigrescens, Polysiphonia urceolata* and *Gracilaria verrucosa.*

In general, the algae recorded on the Solent structures were very similar to those recorded on other stationary floating structures around the British Isles in particular buoys (see especially Grieve and Robertson, 1864; Milne, 1940; Lodge, 1949) and shallow immersed panels (see especially Stubbings and Houghton, 1964; Fletcher, 1974). For example 17 out of the 22 species listed by Lodge (1949) on buoys for the Isle of Man were recorded in the present study, as well as over half of the total number of species recorded on Clyde Sea buoys by Grieve and Robertson (1864), on Tamar Estuary buoys by Milne (1940), and on test panels in Chichester Harbour by Stubbings and Houghton (1964) and in Langstone and Poole Harbours by Fletcher (1974). In addition very similar dominant algae to those presently recorded were reported on many of these structures, e.g. Grieve and Robertson (1864) reported *Ectocarpus, Giffordia, Laminaria* and *Polysiphonia* as being dominant whilst Milne (1940) reported filamentous green algae, *Enteromorpha, Polysiphonia* and *Ulva* as the dominant algae. Certainly the flora was very much richer than that reported by Christie (1973) on the antifouled hulls of ships in service.

It is interesting to note, however, that the importance of the above listed algal genera and species as fouling organisms is not only ap-

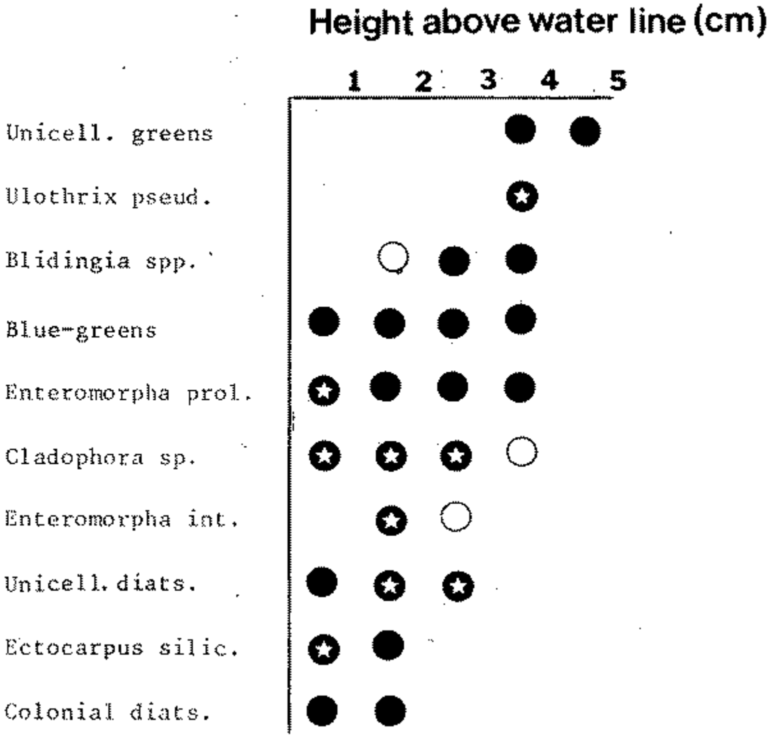

FIG. 26.—Swanwick Marina. Vertical distribution of marine algae. February. Outer Region. Transect 1.

plicable to the British Isles and to floating structures; many of the algae are also widely reported as important fouling organisms on a world wide basis, both on fixed as well as floating structures. Included among the green algae commonly reported are *Enteromorpha*, and in particular *Enteromorpha intestinalis* and *Enteromorpha linza* (Bastida, 1968, 1972; Dabini-Oliva, 1973; Haderlie, 1968 *b*, 1972; Kawahara, 1963; Lyle, 1926, 1929; Pyefinch, 1945; Rossi *et al.*, 1970), *Ulva*, and in particular *Ulva lactuca* (Bastida, 1968, 1972; Dubern, 1967; Long, 1972; Lyle, 1926, 1929; O'Neill and Wilcox, 1971; Skerman, 1960), filamentous algae such as *Ulothrix* and *Urospora* (Daniel, 1955; Meadows, 1969; *Rossi et al.*, 1970; Stubbings and Houghton, 1964), *Cladophora* (see especially Bastida, 1968, 1972; Christie, 1973; Dybern, 1967; Kawahara, 1962; Meadows, 1969; Stubbings and Houghton, 1964) and *Bryopsis* (Bastida, 1968; Ralph and Hurley, 1952; Relini and Dabini-Oliva, 1973; Rossi *et al.*, 1970; Stubbings and Houghton, 1964). Among the brown algae, the genera *Ectocarpus* (see Aleem, 1957; Christie, 1973; Kawahara, 1962; Millard, 1952; O'Neill and Wilcox, 1971), *Giffordia* (Haderlie, 1968 *a*, *b*; Rossi *et al.*, 1970; Stubbings and Houghton, 1964), *Petalonia* (Haderlie, 1968; Lodge, 1949; Rossi *et al.*, 1970) and *Laminaria* (DePalma, 1969; Goodman and Ralph, 1979; Ralph and Goodman, 1979; Stubbings and Houghton, 1964; Withers and Thorp, 1977) are widely reported whilst in the red algae the genera *Polysiphonia* (Aleem, 1957; Bastida, 1968, 1972; Dybern, 1967; Haderlie, 1968 *a*, *b*; O'Neill and Wilcox, 1971; Rossi *et al.*, 1970), *Ceramium* (Bastida, 1968, 1972; Dybern, 1967; Millard, 1952; Rees, 1940; Rossi *et al.*, 1970), *Antithamnion* (Ralph and Hurley, 1952; Rossi *et al.*, 1970) and *Callithamnion* (Lyle, 1926,

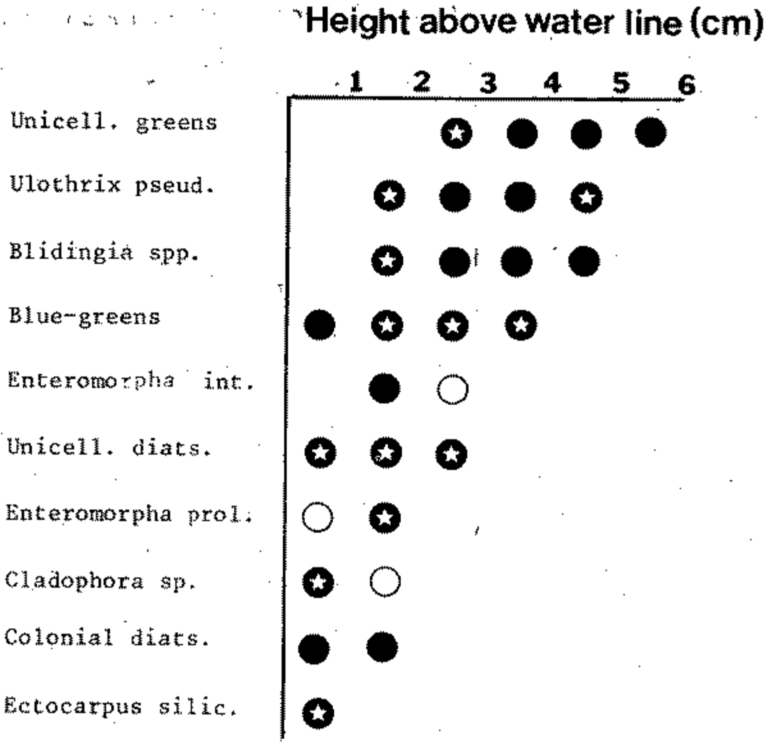

FIG. 27.—Swanwick Marina. Vertical distribution of marine algae. February. Outer Region. Transect 2.

1929; Milne, 1940; Stubbings and Houghton, 1964) are also widely renown.

In many respects the environment provided by the sides of the floating structures in the Solent appears to bear some resemblance to that of the relatively stable subtidal zone. Attached organisms are not, for instance, subjected to tidal phenomenon and should, therefore, essentially be free of the usual environmental stresses such as desiccation, changes in hydrostatic pressure, light intensity and light quality which are associated with the physical rise and fall of the tide. In addition organisms are not likely to be exposed to any severe wave action, sand scouring, particle sedimentation or grazer activity. Probably the only apparent inter-tidal aspect of the environment is the constant relatively high level of illumination which is present. It might be expected, therefore, that this essentially subtidal regime would be reflected in the composition of the fouling community on the float sides and this was borne out by observations on the lower permanently immersed regions. The abundance of animals such as barnacles, tube worms, bryozoans, tunicates and sponges covering the surface, beneath a canopy of large *Laminaria* spp. and smaller brown algae such as *Desmarestia viridis,* green algae such as *Bryopsis plumosa, Derbesia* sp. and *Ulva lactuca* and red algae such as *Ceramium* spp., *Chondrus, Griffithsia and Polysiphonia* spp. is essentially very typical of subtidal communities occurring on hard substrata on the south coast of England.

Of particular importance, however, was the occurrence of a quite distinct community of fouling organisms occupying the water line and higher wave washed regions of the float sides. With the exception of nematodes and protozoa this community was almost exclusively comprised of algae and in particular members of the Chlorophyta. Commonly occurring

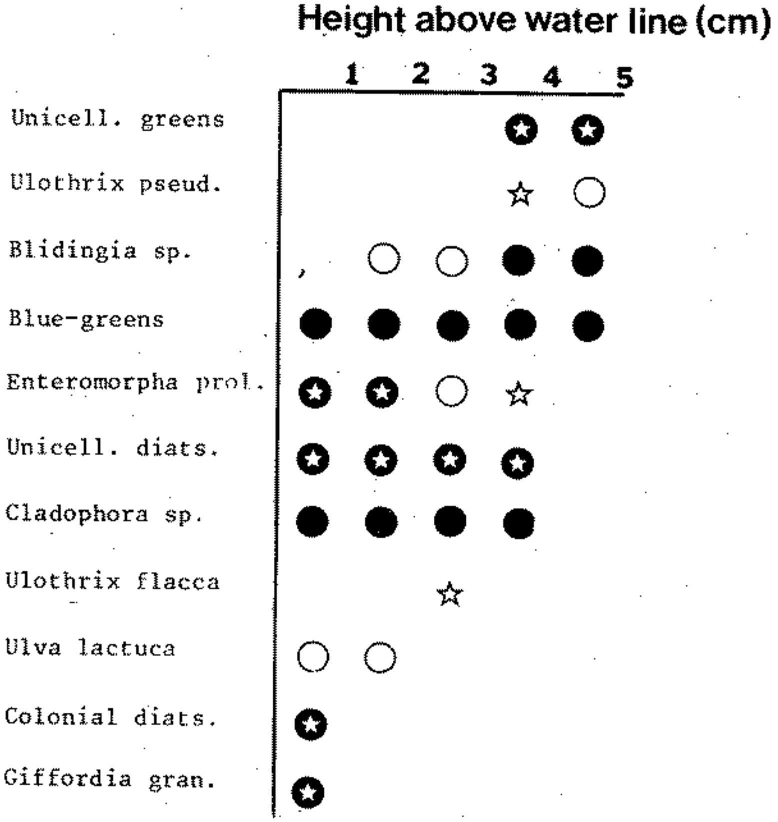

FIG. 28.—Swanwick Marina. Vertical distribution of marine algae, August. Outer Region. Transect 1.

green algal genera included *Blidingia, Cladophora, Derbesia, Enteromorpha, Rhizoclonium, Ulothrix* and *Urospora* whilst common brown algal genera included *Ectocarpus, Giffordia, Petalonia, Pilayella* and common red algae included *Bangia, Chondrus* and *Porphyra*. The occurrence of a water line region dominated by green algae on floating structures is not an unusual phenomenon and has frequently been reported in previous studies (Anon, 1952; Caspers, 1953; Fraser, 1938; Harris, 1946; Milne, 1940; Skerman, 1960; Visscher, 1928, and Tittley and Price, 1977).

Perhaps not surprisingly the vertical extent of the wave washed community above the water line was strongly determined by the degree of wave/current action buffeting the float sides. The inner sheltered walls of the floats in both Gosport and Langstone Harbours, for instance, had a very reduced wave washed community between 3-5 cm in height, whereas a community 40-50 cm in height was common place on the outer exposed Langstone Harbour raft walls. Even more extensive wave washed communities occur on buoys present in the outer regions of the Solent (personal observation). The vertical extent of the wave washed algal community was also slightly influenced by the surface texture of the floats; roughened regions of the Langstone and Fairey floats effectively «raised» the algal community above the level observed on the adjacent smooth surfaces, probably as a result of their enhanced moisture retaining properties.

The upward extension of the algal community in exposed localities also not only

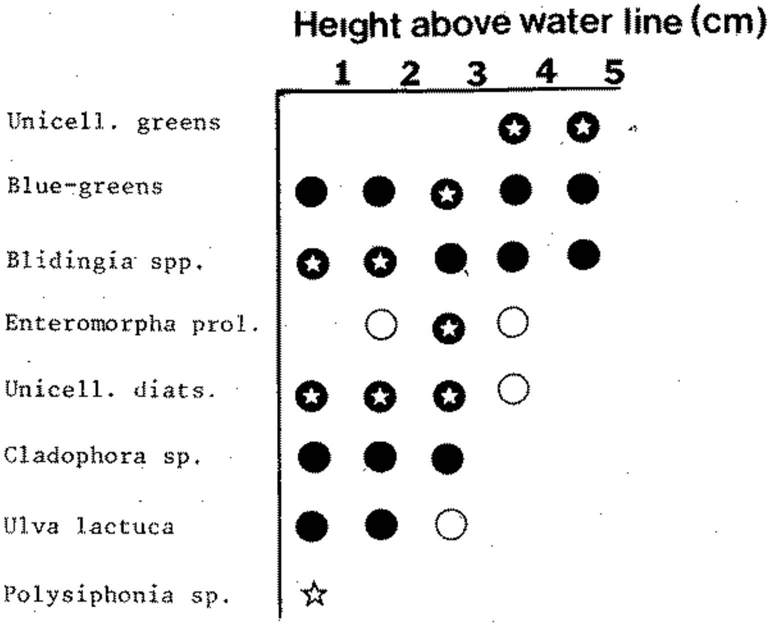

FIG. 29.—Swanwick Marina. Vertical distribution of marine algae. August. Outer Region. Transect 2.

noticeably overall increased the floristic composition of this wave washed region, mainly by «raising» numerous algae, and in particular red and brown algae up from the water line, but appeared to play a part in determining it as well. For example whereas the green algae *Cladophora* sp., *Percursaria percursa, Rhizoclonium riparium, Ulothrix pseudoflacca* and to a lesser extent *Derbesia* sp. were commonly present in sheltered regions, these were largely replaced by the green algae *Enteromorpha linza, Ulothrix flacca, Ulva lactuca* and *Urospora penicilliformis,* the brown algae *Petalonia fascia, Petalonia zosterifolia, Scytosiphon lomentaria* and the red algae *Bangia atropurpurea, Polysiphonia brodiaei* and *Porphyra umbilicalis* in the more exposed regions. It is also noteworthy that the degree of exposure influenced the composition of the lower permanently submerged regions of the floats; the more exposed floats supported good growths of *Laminaria* spp., including *Laminaria digitata,* with occasional large red algae and an underfauna of barnacles and tube worms present; on the sheltered float sides, however, *Laminaria* thalli were less evident and the surface was largely covered by tube worms, tunicates and bryozoans with an extensive low sward of secondary fouling algae such as *Antithamnion plumula, Bryopsis plumosa, Cladophora* sp., *Derbesia* sp., *Griffithsia corallinoides* and *Nitophyllum punctatum.*

Of additional interest was the zoned nature of the algal fouling community present on the wave washed regions of the floats. Essentially up to 6 zones were recognised, this being much more apparent in the more exposed fully marine localities; these consisted of, from the top downwards:

1. A zone dominated by unicellular and coccoid green algae.
2. A zone dominated by filamentous green algae, e.g. *Rhizoclonium, Ulothrix, Urospora,* sometimes with the red algae *Bangia* and *Porphyra* also present.
3. A zone dominated by *Blidingia* spp.
4. A zone dominated by *Enteromorpha* spp., in particular *Enteromorpha prolifera* in the upper regions and *Enteromorpha linza* in the lower regions, with

brown algae such as *Petalonia* and *Ectocarpus* often occurring.

5. A zone dominated by a mixture of *Enteromorpha linza* and various ectocarpoid brown algae such as *Ectocarpus siliculosus, Giffordia granulosa* and *Pilayella littoralis*.
6. A zone dominated by red algae such as *Callithamnion tetragonum, Ceramium rubrum* and *Chondrus crispus* along with brown algae such as *Giffordia granulosa* and green algae such as *Ulva lactuca* and *Cladophora* sp.

Only Milne (1940) in a study of fairly sheltered buoys in the Tamar estuary (south west coast of England) has similarity described the occurrence of a stratified algal community at the water line region; the principal 3 zones which he outlined, comprising, from the top downward, a filamentous green algal dominated zone, a mixed *Enteromorpha* and *Ulva* dominated zone and a red algal dominated zone, are essentially in agreement with the findings of the present study.

In general the algal composition of the upper wave washed float regions shows marked affinity with that of an intertidal shore region, as pointed out by Tittley and Price (1977). Many of the green algal general such as *Blidingia, Enteromorpha, Ulothrix* and *Urospora,* the red algal genera *Bangia* and *Porphyra* and brown algal species such as *Petalonia zosterifolia* are common constituents of the upper littoral regions of many North Atlantic shores (for examples see Lewis, 1953; Gillham, 1954; Klavestad, 1978; Sundene, 1953; Rees, 1940). Similarity has also been shown (see Milne, 1941) between the zonation pattern found on the floating structures and that occurring on many shores (see, for example, shore studies by Den Hartog, 1959; Klavestad, 1978; Nienhuis, 1969; Van den Hoek, 1958). This is perhaps not surprising as the upper regions of both floating structures and shores are relatively unstable habitats in which marine organisms are subjected to considerable fluctuating environment stress and, in particular, to that of desiccation. As the periodic rise and fall of the different tides determines stratification of communities on the shore, so will the frequency and strength of the wave wash determine the algal zoning on the float sides.

The studies on the fouling organisms occupying the sides of the marina floats in the estuarine waters of the Hamble revealed that a much reduced algal community was present compared to that recorded in the fully marine harbours of Langstone and Portsmouth. For example, 36 algae were recorded at the lower situated Fairly Marina compared to 57 and 58 at the Portsmouth and Langstone Harbour sites respectively. The numbers of fouling algae recorded on the float sides also gradually became less numerous in an up-river direction, with 32 algae recorded at the Port Hamble Marina, 29 algae recorded at the Mercury Marina and only 23 algae recorded at the Swanwick Marina. Green algae appeared to be particularly adaptable to the euryhaline waters of the Hamble river with many species widely and commonly distributed on the float sides; these included *Blidingia* spp., *Bryopsis plumosa, Chaetomorpha linum, Cladophora* sp., *Enteromorpha intestinalis, Enteromorpha prolifera, Rhizoclonium riparium, Ulothrix flacca, Ulothrix pseudoflacca* and *Ulva lactuca*. Common red algae extending up-river included *Ceramium rubrum, Chondrus crispus, Polysiphonia elongata, Polysiphonia nigrescens* and *Polysiphonia urceolata,* whilst common brown algae were *Ectocarpus siliculosus, Fucus* sp., *Giffordia granulosa* and *Petalonia fascia*. A reduced number of fouling species has also been reported on buoys in the upper regions of both the Tamar (Milne, 1941) and the Clyde rivers (Grieve and Robertson, 1864). Further, many of the genera listed in these investigations are similar to those presently reported on the floats in the Hamble river; genera commonly reported up-river by Milne (1941) included *Callithamnion, Ceramium, Enteromorpha, Laminaria, Polysiphonia* and *Ulva* whilst genera reported by Grieve and Robertson (1864) included *Ceramium, Chorda, Chordaria, Enteromorpha, Giffordia* (as *Ectocarpus*), *Laminaria, Porphyra, Polysiphonia* and *Ulva*.

Very few seasonal changes were observed in the floristic composition and structure of the floats, this remaining fairly stable both above and below the water line throughout the winter and summer sampling periods.

Some small differences were, however, noted in the abundance of some species colonising the more unstable upper wave washed regions. This community appeared to be more prominent in the winter period, with algae such as *Bangia fuscopurpurea, Enteromorpha linza, Petalonia fascia, Petalonia zosterifolia, Porphyra umbilicalis, Scytosiphon lomentaria, Ulothrix flacca, Ulothrix pseudoflacca, Urospora penicilliformis* and both unicellular and colonial diatoms becoming less abundant during the more adverse summer conditions. A similar winter/spring occurrence of many of the above species, particularly those belonging to the genera *Bangia, Petalonia, Porphyra, Scytosiphon, Ulothrix* and *Urospora* has already been well documented for the upper littoral regions of many North Atlantic shores (Borgesen, 1905; Cotton, 1912; Den Hartog, 1968; Gillham, 1954; Klavestad, 1978; Kristiansen, 1972).

SUMMARY

A study has been made of the composition and structure of marine algal fouling communities present on the vertical sides of variously exposed floating structures (pontoons/rafts) in the Solent, south coast of England, during February (winter period) and August (late summer period), 1979. Three localities were investigated; the two fully marine harbours of Portsmouth and Langstone and the lower estuarine region of the river Hamble.

Two distinct fouling communities are described:

1. A lower, permanently submerged community usually dominated by *Laminaria* spp., with an underflora of various red algae (e.g. *Ceramium, Chondrus, Griffithsia, Polysiphonia*) brown algae (*Desmarestia*) and green algae (*Bryopsis, Cladophora, Derbesia, Ulva*) and a well developed underfauna of barnacles, tube worms, tunicates and tube dwelling amphipods. The components of this community are similar to those found on natural hard substrata in the subtidal regions of the Solent.

2. An upper wave washed community largely dominated by green algae, such as *Blidingia, Enteromorpha, Rhizoclonium, Ulothrix, Urospora* but including various brown algae such as *Ectocarpus, Giffordia, Petalonia, Scytosiphon* and red algae such as *Bangia, Ceramium* and *Porphyra*. The components of this community, on the other hand, are more similar to those found on natural hard substrate in the upper littoral regions of shores.

Both the vertical extent and composition of the upper wave washed algal community on the float sides was strongly determined by the degree of exposure to wave/current action. On sheltered floats, in fully marine habitats the community only extended 20-50 mm above the water line and was composed of a relatively small number of algae such as *Blidingia, Cladophora, Enteromorpha, Rhizoclonium* and *Ulothrix*. On the more exposed floats studied the community extended in excess of 400 mm above the water line and supported a much greater variety of algae including *Acinetospora, Bangia, Blidingia, Cladophora, Ectocarpus, Enteromorpha, Giffordia, Petalonia, Pilayella, Polysiphonia, Porphyra, Scytosiphon, Ulothrix* and *Urospora*.

A distinct vertical zonation of algae occurred on the wave washed regions, this being particularly evident in the fully marine exposed localities, where up to 6 horizontal bands or associations of algae were detected; from the top downwards these consisted of bands of unicellular green algae, filamentous green algae (especially *Ulothrix, Urospora*), *Blidingia* spp., *Enteromorpha* spp., (*Enteromorpha intestinalis, Enteromorpha prolifera*), brown algae (*Ectocarpus, Petalonia*) and, at the water line, red algae (*Ceramium, Chondrus*).

The more euryhaline waters of the Hamble estuary generally supported a much reduced flora compared to that present in the fully marine localities, and this became more pronounced in an up-river direction. Green algae

appeared to be particularly tolerant of salinity changes, with many genera such as *Blidingia, Bryopsis, Enteromorpha, Rhizoclonium, Ulothrix* and *Ulva* widely and commonly reported. Euryhaline brown algae included *Ectocarpus, Giffordia* and *Petalonia,* whilst euryhaline red algae included *Ceramium, Chondrus* and *Polysiphonia.*

Some seasonal changes were observed in the composition of the fouling algal communities, particularly that of the upper more exposed wave washed regions. A pronounced winter/spring community comprised of *Bangia atropurpurea, Enteromorpha linza, Petalonia* spp., *Porphyra umbilicalis, Ulothrix* spp. and *Urospora penicilliformis,* unicellular and colonial diatoms were usually present in these upper regions, which appeared to diminish during the summer period.

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LOS BRIOZOOS DE LAS COMUNIDADES INCRUSTANTES DE PUERTOS ARGENTINOS

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RESUMEN

En el presente trabajo se describen los briozoos identificados hasta el momento en las comunidades incrustantes de varios puertos de la costa bonaerense: Mar del Plata, Puerto Quequén y Puerto Belgrano.

En la provincia de Buenos Aires no existen antecedentes sobre estudios sistemáticos de briozoos y las únicas referencias sobre el grupo son aquellas que figuran en los trabajos sobre incrustaciones biológicas que se vienen desarrollando desde 1965.

Se citan y describen un total de once especies: *Alcyonidium polyoum, Bowerbankia gracilis, Bowerbankia imbricata, Scruparia ambigua, Conopeum reticulum, Bugula neritina, Bugula flabellata, Bugula simplex, Bugula stolonifera, Cryptosula pallasiana* y *Crisia eburnea.*

Todas ellas constituyen nuevas citas formales para la provincia de Buenos Aires; cuatro especies no habían sido citadas previamente para Argentina, ampliándose de esta forma su límite austral de distribución geográfica.

Se incluyen asimismo ilustraciones de las colonias y, como complemento, fotografías obtenidas con el microscopio electrónico de barrido. También se brinda una clave para el reconocimiento de los diferentes géneros y claves parciales para los casos en que existe más de una especie del mismo género.

Por último, se incluye un glosario, a fin de facilitar la consulta del trabajo por parte de los no especialistas en el grupo.

INTRODUCCION

Los briozoos constituyen uno de los grupos de invertebrados marinos poco conocidos en la Argentina. La mayor parte de los estudios existentes sobre el tema han sido realizados por investigadores extranjeros en base al material coleccionado en expediciones antárticas y subantárticas.

Entre los trabajos llevados a cabo por investigadores argentinos pueden mencionarse los realizados en la ría de Puerto Deseado (Amor y Pallarés, 1965), en la zona de Tierra del Fuego (López Gappa, 1975, 1977 *a*) y otras contribuciones más restringidas (López Gappa, 1977 *b;* Amor, 1978). Merece destacarse también la reciente publicación de un catálogo preliminar de briozoos y entoproctos actuales de la Argentina (López Gappa, 1978).

A lo largo de las extensas costas argentinas existen zonas totalmente desconocidas en cuanto a su fauna briozoológica. Una de ellas es la provincia de Buenos Aires, donde los únicos antecedentes al respecto son las citas incluidas en los trabajos sobre incrustaciones biológicas realizados en Mar del Plata, Puerto Belgrano y Puerto Quequén por el equipo de investigación que integran los autores.

Cabe señalar que los briozoos son importantes componentes de las comunidades incrus-

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tantes, llegando incluso a ser dominantes durante ciertas etapas sucesionales de las mismas. Su presencia está, por tanto, relacionada con aspectos eminentemente prácticos y de considerable repercusión económica. Debido a la variedad de hábitos que presentan estos organismos, el papel que desempeñan dentro de la comunidad es también variable, condicionando procesos de diferente tipo en las estructuras sumergidas.

El presente trabajo constituye un nuevo aporte al conocimiento de los briozoos de las costas argentinas. En él se describen las especies encontradas hasta el momento sobre balsas experimentales fondeadas en varios puertos de la provincia de Buenos Aires. Esta información permite, además, completar el conocimiento sistemático de otro de los grupos que integran las comunidades incrustantes locales, lo cual resulta fundamental para la experimentación y evaluación de sistemas de control antiincrustante.

Se pretende asimismo que este trabajo pueda ser utilizado como una guía práctica para los investigadores no familiarizados con el grupo y que deseen encarar estudios de tipo ecológico en la zona. Es por ello que el vocabulario se ha simplificado al máximo, evitando en lo posible la complicada terminología que abunda en la literatura especializada.

MATERIAL Y METODOS

El material examinado proviene de las muestras obtenidas sobre paneles experimentales a lo largo de varios años en tres localidades de la costa bonaerense: Mar del Plata (38° 03' S, 57° 31' W), Puerto Belgrano (38° 54' S, 62° 06' W) y Puerto Quequén (38° 36' S, 58° 40' W).

La metodología empleada en los estudios de comunidades incrustantes ya ha sido exhaustivamente descrita en trabajos anteriores (Bastida, 1970, 1971, 1972). Sólo cabe aclarar que se utilizan dos tipos de paneles: los llamados mensuales, que permanecen sumergidos por períodos de treinta días a lo largo de un ciclo anual y a través de los cuales es posible determinar los ciclos de fijación de las diferentes especies, y los paneles acumulativos, que se sumergen por períodos progresivamente más largos, desde un mes hasta el final del período experimental; en este caso, un año. La información obtenida a través de los paneles acumulativos permite conocer la evolución de la comunidad incrustante a lo largo del tiempo y los procesos de sucesión ecológica que en ella tienen lugar.

Las especies descritas son las siguientes:

1. *Alcyonidium polyoum* (Hassall).
2. *Bowerbankia gracilis* Leidy.
3. *Bowerbankia imbricata* (Adams).
4. *Scruparia ambigua* (d'Orbigny).
5. *Conopeum reticulum* (Linnaeus).
6. *Bugula neritina* (Linnaeus).
7. *Bugula flabellata* (Thompson).
8. *Bugula simplex* Hincks.
9. *Bugula stolonifera* Ryland.
10. *Cryptosula pallasiana* (Moll).
11. *Crisia eburnea* (Linnaeus).

Los ejemplares estudiados fueron limpiados con pincel bajo estereomicroscopio y, en el caso de las colonias bien calcificadas, sumergidos en una solución de hipoclorito de sodio según las técnicas clásicas. Los dibujos se realizaron bajo microscopio con la ayuda de una cámara clara. Para el estudio de algunas especies se recurrió al empleo del microscopio electrónico de barrido, técnica que se adapta perfectamente a este tipo de material.

En la descripción de cada especie se incluye la cita original, las correspondientes a aguas argentinas, en caso de que existan, y las utilizadas en la determinación sistemática y obtención de datos de distribución.

También se presenta una clave para el reconocimiento de los diferentes géneros encontrados en la zona de estudio y claves parciales en el caso en que se describen más de una especie para un mismo género.

A los efectos de facilitar el uso de la clave y la interpretación de las descripciones a aquellos no familiarizados con el grupo se incluye un breve glosario de la terminología empleada.

AREA DE ESTUDIO

La zona eminentemente costera de la provincia de Buenos Aires se caracteriza por presentar una fauna de briozoos poco abundante y escasamente diversificada. Sin embargo, las comunidades bentónicas que habitan las áreas portuarias de esta zona suelen presentar una mayor abundancia y diversidad de briozoos. Esta situación ha sido observada en otras partes del mundo y son frecuentes los casos de especies que prosperan en estructuras portuarias y paneles experimentales, pero que están ausentes o poco representadas en las zonas naturales aledañas.

Las tres áreas portuarias estudiadas pertenecen biogeográficamente a la provincia argentina. Se trata de una zona de clima templado, lo que condiciona claras fluctuaciones estacionales en sus factores ambientales.

CLAVE PARA EL RECONOCIMIENTO DE LOS GENEROS DE BRIOZOOS DE LAS COMUNIDADES INCRUSTANTES DEL PUERTO DE MAR DEL PLATA, PUERTO QUEQUEN Y PUERTO BELGRANO

1.	Colonias totalmente adheridas al sustrato, formando una capa de zooecios calcificados	2
—.	Colonias no de tipo incrustante; si son de tipo incrustante, los zooecios no están calcificados	3
2.	Zooecios en forma de caja, con la superficie frontal membranosa; frecuentemente con un par de áreas triangulares en los ángulos proximales de los zooecios	*Conopeum*
—.	Zooecios con superficie frontal calcificada (excluyendo el orificio, que se cierra por un opérculo), opaca, perforada por numerosos poros	*Cryptosula*
3.	Colonias erectas, ramificadas; zooecios con o sin avicularias	4
—.	Colonias incrustantes o estolonadas rastreras; avicularias nunca presentes.	5
4.	Colonias con ramas flexibles formadas por series de dos o más zooecios, parcialmente calcificados; avicularias generalmente presentes; con ovicelas en los ejemplares fértiles	***Bugula***
—.	Colonias con ramas rígidas, articuladas por uniones de tipo quitinoso; zooecios tubulares, completamente calcificados; orificio terminal aproximadamente circular, sin opérculo; sin avicularias	***Crisia***
5.	Colonias incrustantes, no calcificadas, formando una capa blanda sobre el sustrato; zooecios poligonales, contiguos	*Alcyonidium*
—.	Colonias de tipo rastrero, formadas por estolones adherentes o parcialmente libres, de los cuáles nacen zooecios individuales, en grupos o en cadenas; avicularias nunca presentes	6
6.	Zooecios o cadenas de zooecios que nacen de un estolón adherente o de una hilera de zooecios, también adherente	*Scruparia*
—.	Zooecios de forma cilíndrica con orificio terminal; los zooecios nacen individualmente, de a pares o en manojos sobre estolones adherentes o parcialmente libres	*Bowerbankia*

El puerto de Mar del Plata se caracteriza por presentar una marcada variación en la temperatura del agua, con un rango anual de aproximadamente 12° C en temperaturas medias mensuales; la máxima suele superar levemente los 20° C, mientras que la mínima puede estar por debajo de los 10° C. Los valores de salinidad no presentan fluctuaciones estacionales, pudiendo ser algo inferores a los de las zonas aledañas, si bien nunca se encuentran por debajo de 31 ‰. En virtud de la intensa contaminación por materia orgánica que existe en la zona, el pH del agua es generalmente inferior al del agua de mar normal; los valores se encuentran, por lo común, alrededor de pH = 7, y en períodos críticos o en zonas más internas del puerto se registran valores de hasta pH = 6. Como consecuencia de los problemas de contaminación mencionados anteriormente, unidos a la baja turbulencia de la zona portuaria y la mala renovación de sus aguas, los valores de O_2 disuelto también suelen ser inferiores a los normales.

En cuanto a Puerto Quequén, puede decirse que se trata de una zona con características particulares, ya que está ubicada en la desembocadura del río Quequén y sujeta, por tanto, a influencias de masas de agua de distinto origen. La variación de temperatura del agua es similar a la descrita para el puerto de Mar del Plata. Un aspecto que diferencia netamente a este puerto del anterior es la variación en la salinidad. Por influencia de las mareas se producen fluctuaciones diarias muy notables, con rangos de hasta 20 ‰. Los valores máximos anuales son del orden de 35 ‰, mientras que en épocas de lluvias se registran mínimos de alrededor de 2,5 ‰. Los valores de pH, en cambio, se presentan en forma uniforme a lo largo del año y están levemente por encima de pH = 8.

Por último, Puerto Belgrano está ubicado en una zona con características de ría, que podrían considerarse intermedias entre las que presentan Mar del Plata y Puerto Quequén. El patrón de variación térmica no difiere mayormente del observado en los otros puertos estudiados, mientras que la salinidad en algunas oportunidades puede presentar valores relativamente bajos (25 ‰). Al igual que en Puerto Quequén, no se observan descensos notables en el pH del agua. Por el tipo de fondos que predominan en la zona, las aguas suelen tener a lo largo de todo el año un mayor contenido de sedimentos en suspensión que las áreas mencionadas anteriormente.

Las especies identificadas en las comunidades incrustantes locales presentan una amplia distribución geográfica a nivel mundial e integran las incrustaciones biológicas de áreas portuarias muy diversas. Se trata generalmente de especies cuya distribución natural se ha visto favorecida por el transporte transoceánico a través de embarcaciones.

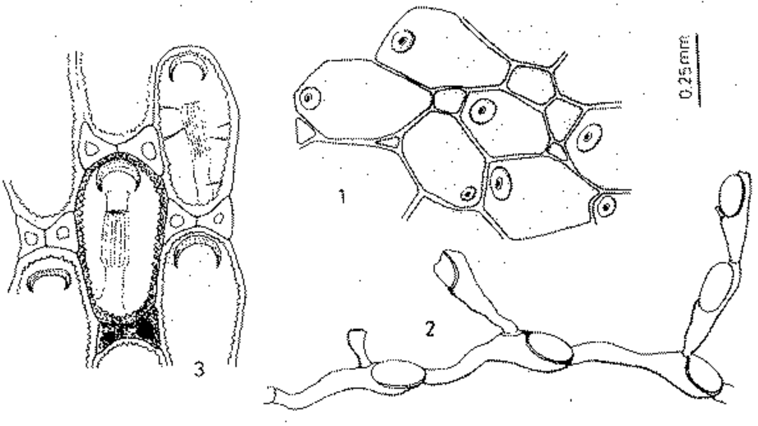
Por tanto, los datos de distribución geográfica que se incluyen al final de las descripciones se limitan a las cifras previas para Argentina, y en su defecto se hace referencia al límite de distribución austral conocido hasta el momento para el Atlántico occidental.

— PHYLUM BRYOZOA Ehrenberg, 1831.
— Clase GYMNOLAEMATA Allman, 1856.
— Orden CTENOSTOMATA Busk, 1852.
— Suborden CARNOSA Gray, 1841.
— Superfamilia HALCYONELLOIDEA Johnston, 1847.
— Familia ALCYONIDIIADE Johnston, 1849.
— Género *Alcyonidium* Lamouroux, 1812.

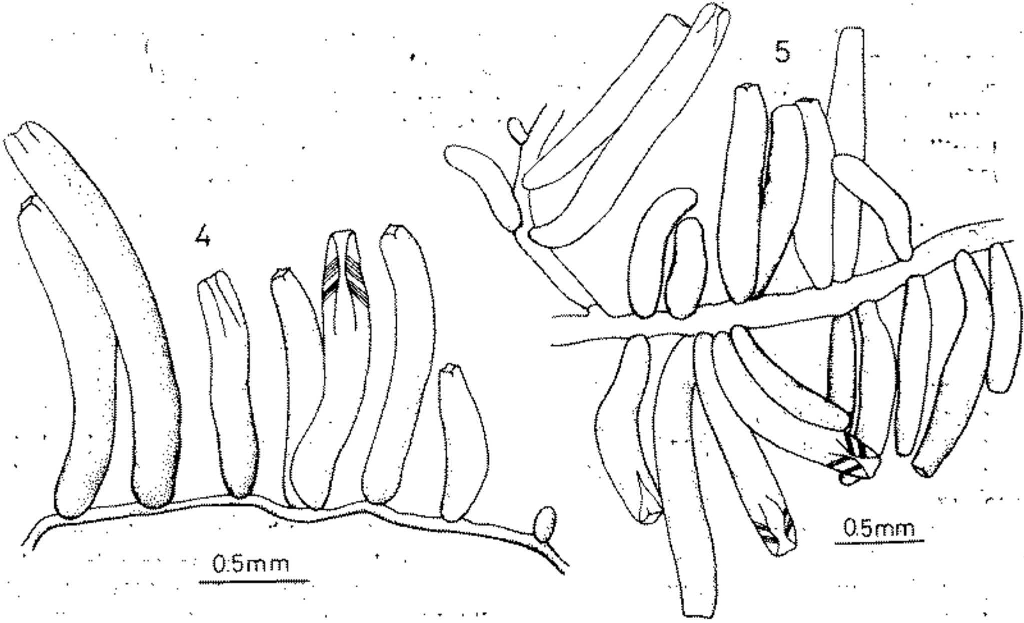
Alcyonidium polyoum (Hassall, 1841)

Sarcochitum polyoum Hassall, 1841: 484.
Alcyonidium mytili, Calvet, 1904: 38.
Alcyonidium polyoum, Marcus, 1937: 125.
Alcyonidium mytili, Osburn, 1912: 251.
Alcyonidium polyoum, Osburn, 1947: 6.
Alcyonidium polyoum, Rogick y Croasdale, 1949: 45.
Alcyonidium polyoum, Osburn y Soule, 1953: 727.
Alcyonidium polyoum, Le Brozec, 1955: 37.
Alcyonidium polyoum, Maturo, 1957: 18.
Alcyonidium polyoum, Amor y Pallarés, 1965: 299.

Colonias incrustantes de consistencia blanda, nunca erectas, constituyendo una capa delgada que adopta la forma del sustrato al que se adhiere, de color pardo, pardo-amarillento o pardo-grisáceo. Zooides generalmente hexagonales, subcuadrangulares o pentagonales, de extremos redondeados, a veces algo alargados, contiguos y de superficie lisa; el límite entre los zooides es fácilmente diferenciable, sobre



FIGS. 1, 2 y 3.—1. *Alcyonidium polyoum,* porción de una colonia en vista frontal. 2. *Scruparia ambigua,* aspecto general de una colonia. 3. *Conopeum reticulum,* porción de una colonia en vista frontal.



FIGS. 4 y 5.—4. *Bowerbankia gracilis.* Aspecto de una porción de la colonia. 5. *Bowerbankia imbricata.* Aspecto de una porción de la colonia.

todo en las colonias jóvenes; superficie frontal amplia, con el orificio excéntrico y ubicado a menudo sobre una pequeña papila. Polipidio con 14-20 tentáculos, apenas visible a través de la pared frontal.

Observaciones

Se trata de una especie poco abundante en las muestras analizadas y que, por otra parte, no presenta mayor importancia en las comunidades incrustantes. Ha sido registrada exclusivamente en la zona de Puerto Belgrano, donde se la encontró sobre otros briozoos (*Cryptosula pallasiana, Bugula neritina, Conopeum reticulum*), tunicados (*Ciona intestinalis, Botryllus schlosseri*), cirripedios (*Balanus amphitrite*) e hidrozoos (*Plumularia setacea*).

Cabe mencionar que es probable que existan en Puerto Belgrano otras especies de *Alcyonidium*, aspecto que será confirmado en base a nuevo material actualmente en estudio.

En Argentina ha sido registrada en la zona de la ría Deseado (Amor y Pallarés, 1965) y citada como *Alcyonidium mytili* para Tierra del Fuego (Calvet, 104). En la provincia de Buenos Aires no había sido citada previamente en trabajos de índole sistemática.

- Suborden Stolonifera Ehlers, 1876.
- Superfamilia Vesicularioidea Johnston, 1847.
- Familia Vesiculariidae Johnston, 1838.
- Género *Bowerbankia* Farre, 1837.

Bowerbankia gracilis Leidy, 1855
(fig. 4)

Bowerbankia gracilis Leidy, 1855: 142.
Bowerbankia caudata, Hincks, 1880: 521.
Bowerbankia gracilis, Osburn, 1912: 253.
Bowerbankia caudata, Marcus, 1937: 137.
Bowerbankia caudata, Marcus, 1938: 56.
Bowerbankia gracilis, Osburn, 147: 7.
Bowerbankia gracilis, Rogick y Croasdale, 1949: 47.
Bowerbankia gracilis, Osburn y Soule, 1953: 744.
Bowerbankia gracilis, Maturo, 1957: 25.
Bowerbankia gracilis, Ryland, 1965: 78.
Bowerbankia gracilis, Amor y Pallarés, 1965: 298.

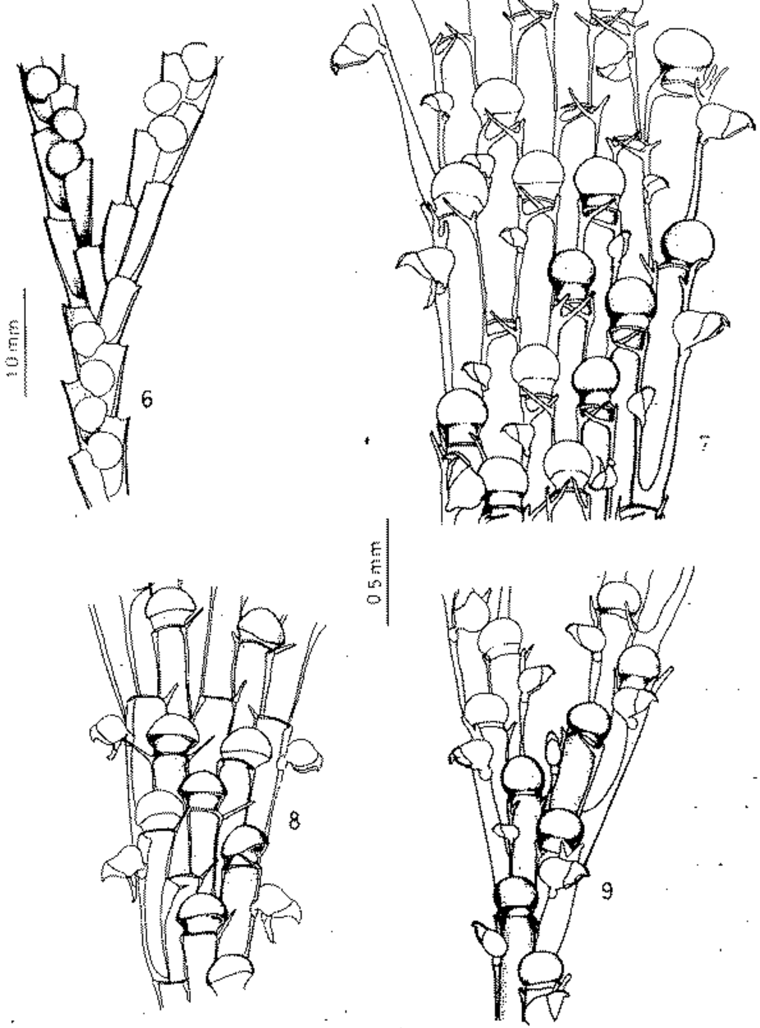
Colonias con un estolón adherente, irregularmente ramificado y delgado, del cual se originan los zooides, que son erectos; en su conjunto, las colonias se presentan como una masa blanquecina o grisácea, de aspecto lanoso. Zooides tubulares, delgados, transparentes o algo amarillentos, más estrechos en su parte proximal y distal, de aproximadamente 1,5 mm de largo, aunque ocasionalmente pueden ser más largos; el extremo distal es de forma cuadrangular, más evidente cuando el polipidio está retraído; los zooides nacen generalmente de la parte superior o laterales del estolón, individualmente, de a pares o en pequeños manojos; en la parte proximal del zooecio a veces se observa una proyección o «proceso caudal». El estolón es relativamente más delgado que el ancho de los zooides (hasta 0,1 mm, aproximadamente) y está dividido a ciertos intervalos por septos uniporosos. Polipidio típicamente con ocho tentáculos.

Observaciones

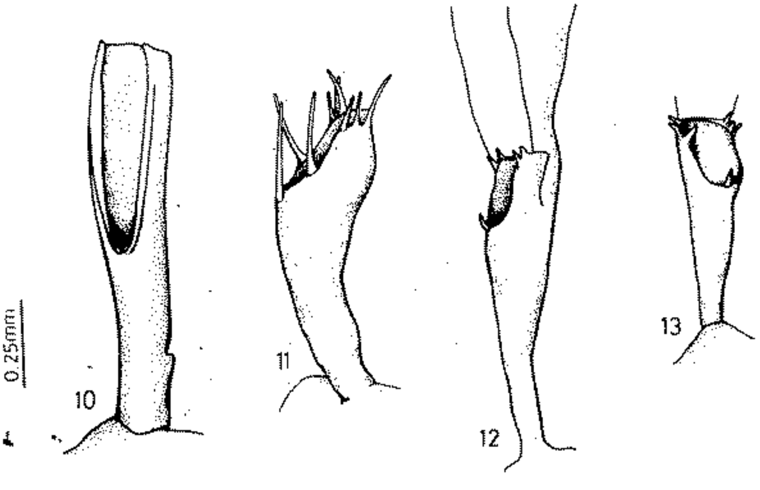
Se trata de una especie bien representada en las comunidades incrustantes del puerto de Mar del Plata y, en menor medida, en las de Puerto Belgrano. Su ausencia en Puerto Quequén puede deberse a las bajas salinidades que caracterizan la zona; sin embargo, por tratarse de un área donde los estudios se han iniciado recientemente, este hecho deberá confirmarse a través de ensayos futuros.

En el puerto de Mar del Plata, *Bowerbankia gracilis* es una especie de fijación estacional, que a lo largo de los años ha presentado variaciones tanto en los períodos como en la densidad de colonización. Es un organismo capaz de integrarse a las comunidades incrustantes en sus etapas sucesionales tempranas, una vez constituida la película inicial. Por otra parte, *B. gracilis,* junto con otros invertebrados, llega a caracterizar ciertas etapas serales de la comunidad, si bien las mismas suelen ser de corta duración.

Esta especie se adhiere tanto a los sustratos experimentales como a otros organismos incrustantes, entre ellos ascidias (*Ciona intestinalis*), hidrozoos (*Tubularia,* Campanulariidae), cirripedios (*Balanus* spp.), tubos de poliquetos (*Polydora ligni*) y algas (*Enteromorpha* spp.).



FIGS. 6, 7, 8 y 9.—6. ***Bugula neritina***, porción de una colonia en vista frontal. 7. ***Bugula flabellata***, porción de una colonia en vista frontal. 8. ***Bugula simplex***, porción de una colonia en vista frontal. 9. ***Bugula stolonifera***, vista frontal de una bifurcación.



FIGS. 10, 11, 12 y 13.—Ancéstrulas de diferentes especies de ***Bugula***. 10. ***Bugula***

En las épocas de mayor abundancia suele formar densas aglomeraciones, que a su vez actúan como sustrato para la fijación de otros organismos de pequeña talla.

En Puerto Belgrano este briozoo no llega a ser tan abundante y su presencia está restringida a los paneles acumulativos, donde se le encuentra principalmente como epibionte sobre tunicados (*Ciona intestinalis, Botryllus schlosseri,* Didemnidae), otros briozoos (*Bugula* spp., *Conopeum reticulum, Alcyonidium polyoum, Cryptosula pallasiana*), hidrozoos (*Tubularia,* Campanulariidae) y algas (*Enteromorpha* spp.).

En la Argentina, *Bowerbankia gracilis* ha sido registrada en la ría Deseada (Amor y Pallarés, 1965). En la provincia de Buenos Aires no había sido citada previamente en trabajos de índole sistemática.

Bowerbankia imbricata (Adams, 1800)
(fig. 5)

Sertularia imbricata, Adams, 1800: 11.
Bowerbankia imbricata, Rogick y Croasdale, 1949: 47.
Bowerbankia imbricata, Osburn y Soule, 1953: 743.
Bowerbankia imbricata, Ryland, 1965: 79.
Bowerbankia imbricata, Amor y Pallarés, 1965: 296.

Colonias con un estolón ramificado, relativamente grueso, adherente o más frecuentemente libre en sus extremos distales, del cual se originan los zooides, que son erectos; las colonias forman una masa densa, blanquecina o algo grisácea, de aspecto lanoso. Zooides de forma tubular u ovoide, más angostos en sus extremos proximal y distal, transparentes o amarillentos, de aproximadamente 1,5 mm de largo; en el extremo proximal pueden presentar una proyección o «proceso caudal»; los zooides están generalmente dispuestos en densos manojos a lo largo del estolón y, en los extremos libres, suelen distribuirse alrededor del mismo. El estolón está dividido a intervalos por septos uniporosos y es bastante más grueso que en *Bowerbankia gracilis* (aproximadamente, 0,2 mm); a menudo, el estolón es difícil de distinguir, debido a la densidad de los zooides. Polipidio típicamente con 10 tentáculos, generalmente visible por transparencia en el interior del zooecio.

OBSERVACIONES

Bowerbankia imbricata y *B. gracilis* son especies muy semejantes y difíciles de diferenciar. Además, pueden colonizar conjuntamente los paneles experimentales formando densas masas, lo que imposibilita una rápida identificación del conjunto. Por otra parte, los caracteres diferenciales, como pueden ser el grosor del estolón y la forma de inserción de los zooides, pueden presentar variaciones de una porción de la colonia a otra. El carácter que, según los diferentes autores y de acuerdo a nuestras propias observaciones, define a ambas especies es el número de tentáculos, que es de ocho en *B. gracilis* y de diez en *B. imbricata.* Sin embargo, tiene el inconveniente de ser de difícil observación en material fijado.

Cabe mencionar que durante los primeros ensayos en el puerto de Mar del Plata no se registraba la presencia de esta especie, siendo abundante, en cambio, *Bowerbankia gracilis.*

CLAVE PARCIAL PARA LAS ESPECIES DE *BOWERBANKIA*

1. Polipidio con ocho tentáculos; zooides solitarios, en pares o en pequeños manojos; estolón adherente, considerablemente más delgado que el ancho de los zooides .... *B. gracilis*

—. Polipidio con 10 tentáculos; zooides generalmente dispuestos en densos manojos; estolón relativamente ancho (0,2 mm. aproximadamente), con frecuencia libre en sus extremos proximal y distal .... *B. imbricata*

Con el correr de los años, su fijación se ha visto incrementada, llegando incluso a ser dominante sobre *B. gracilis*. Al igual que la anterior, es una especie de fijación estacional, que puede integrarse tempranamente a la comunidad incrustante y llega a caracterizar ciertas etapas en la evolución de la misma. Hasta el presente, no ha sido encontrada en las muestras provenientes de Puerto Quequén y Puerto Belgrano.

En la Argentina, *Bowerbankia imbricata* ha sido registrada en la ría Deseado (Amor y Pallares, 1965), y para la provincia de Buenos Aires no había sido citada en trabajos de índole sistemática.

— Orden CHEILOSTOMATA Busk, 1852.
— Suborden ANASCA Levinsen, 1909.
— Superfamilia SCRUPARIOIDEA Silen, 1941.
— Familia SCRUPARIIDAE Busk, 1852.
— Género *Scruparia* Oken, 1815.

Scruparia ambigua (d'Orbigny, 1847)
(fig. 2)

Eucratea ambigua, d'Orbigny, 1847.
Eucratea chelata, Robertson, 1905: 248.
Eucratea chelata, Vallentin, 1924: 373.
Scruparia ambigua, Hastings, 1941: 465-472.
Scruparia ambigua, Hastings, 1943: 475.
Scruparia ambigua, Ryland, 1965: 21.
Scruparia ambigua, Amor y Pallarés, 1965: 309.

Colonias de aspecto delicado, compuestas por una parte rastrera y porciones erectas; la primera consiste de una hilera simple de zooecios adherentes, de los cuales surgen las cadenas libres, también uniseriadas; los zooecios de la serie incrustante dan origen a brotes distales, frontales y laterales; todos ellos dan nuevos zooecios; los frontales surgen del borde proximal del área membranosa y son erectos; los distales y laterales son incrustantes. Zooecios largos y delgados, más estrechos en el extremo proximal y ensanchándose hacia el centro; área membranosa de forma ovalada y casi paralela a la pared basal del zooecio. Ovicelas más pequeñas que el zooide fértil; el área membranosa de este último es más larga que ancha. Ancéstrula apoyada sobre un lado, da origen a brotes distales y frontales de zooecios incrustantes; de éstos surgen las porciones erectas.

OBSERVACIONES

Es ésta una especie poco común en las comunidades incrustantes y se la ha encontrado sólo en las muestras provenientes de Puerto Belgrano, en escasas oportunidades, adherida sobre *Bugula neritina*. Las colonias examinadas no presentaban ovicelas, las que, por otra parte, según Ryland (1965), se observan raramente en esta especie.

En la Argentina, *Scruparia ambigua* ha sido registrada en las islas Malvinas (Vallentin, 1924). Cabo de Hornos y plataforma patagónica (Hastings, 1941, 1943) y en la zona de la ría Deseado (Amor y Pallarés, 1965). En la provincia de Buenos Aires no había sido citada previamente en trabajos de índole sistemática.

— Superfamilia MALACOSTEGOIDEA Levinsen, 1909.
— Familia MEMBRANIPORIDAE Busk, 1854.
— Género *Conopeum* Gray, 1848.

Conopeum reticulum (Linnaeus, 1767)
(figs. 3, 14, 15 y 16)

Millepora reticulum Linnaeus, 1767: 1.284.
Flustra lacroixii, Audouin, 1826: 240.
Membranipora lacroixii, Hincks, 1880: 129.
Membranipora lacroixii, Waters, 1898: 679.
Membranipora lacroixii, Robertson, 1908: 261.
Membranipora lacroixii, Osburn, 1912: 227.
Conopeum reticulum, Harmer, 1926: 211.
Conopeum reticulum, Marcus, 1938: 13.
Conopeum reticulum, Bobin y Prenant, 1962: 383.
Conopeum reticulum, Ryland, 1965: 30.

Colonias incrustantes, de aspecto reticulado y color blanco, formando una capa calcárea sobre el sustrato. Zooecios de forma variable, típicamente más largos que anchos, más o menos hexagonales, con la superficie frontal totalmente ocupada por la membrana frontal; gimnocisto poco desarrollado, densamente cubierto por pequeños tubérculos, que le dan un aspecto granulado; criptocisto de estructura similar, rodeando todo el margen, a veces más ancho en el extremo proximal; los tubérculos del criptocisto se proyectan dentro del opesio, dándole un aspecto denticulado al borde del mismo; pueden observarse a veces algunas espinas delicadas que se proyectan hacia el opesio desde la pared zooecial. Los ángulos proximales del zooecio presentan típicamente un par de cavidades triangulares bien caracterizadas, con una pequeña área membranosa; estas dos cavidades pueden estar fusionadas transversalmente e incluso faltar por completo. Opérculo de estructura compleja; consta de una placa opercular blanda, rodeada en sus bordes distal y laterales por un esclerito fino y una membrana fibrosa. El zooecio presenta una placa multiporosa en la pared distal y dos o tres en las paredes laterales. Ancéstrula simple, similar al zooecio adulto, pero más pequeña. Sin avicularias ni ovicelas.

OBSERVACIONES

Es una especie muy importante en las comunidades incrustantes de Puerto Belgrano. En el puerto de Mar del Plata y Puerto Quequén, si bien se registran frecuentemente representantes del género, aún no se ha dilucidado su ubicación específica.

En Puerto Belgrano este briozoo ha presentado una fijación de tipo anual, con períodos de mayor densidad en octubre y entre febrero y junio. Desempeña un papel muy importante en las primeras etapas sucesionales de la comunidad.

En paneles mensuales, donde la competencia espacial es menor, las colonias de *Conopeum reticulum* se adhieren firmemente al sustrato, formando un delgado tapiz. Sin embargo, en comunidades más desarrolladas, con gran presión espacial, las colonias pueden adoptar formas erguidas (festoneadas, arrepolladas, etc.). En ciertos casos, distintas colonias pueden unirse por sus bases, separándose del sustrato a modo de pequeños pétalos bilaminares. Este tipo de crecimiento se produce asimismo entre colonias de *C. reticulum* y de *Cryptosula pallasiana*, otro briozoo incrustante frecuente en la zona.

Como consecuencia de la falta de espacio, *Conopeum reticulum* también puede crecer sobre otros organismos de la comunidad (*Bugula neritina, Balanus amphitrite, Plumularia setacea,* etc.), llegando en algunos casos a cubrirlos totalmente y adoptando la forma de los mismos. En épocas de gran abundancia, en que este briozoo llega a extenderse ampliamente sobre los paneles experimentales, constituye, a su vez, una importante superficie de asentamiento para otros organismos colonizadores. Sin embargo, aún no se ha podido determinar si la fijación puede producirse sobre porciones vivas de la colonia.

Conopeum reticulum no había sido citado previamente para la Argentina. En el Atlántico occidental, el límite de distribución austral correspondía a Santa Catharina, Brasil (Marcus, 1938, 1939).

— Superfamilia CELLULARIOIDEA Smitt, 1867.
— Familia BUGULIDAE Gray, 1848.
— Género *Bugula* Oken, 1815.

Bugula neritina (Linnaeus, 1758)
(fig. 6)

Sertularia neritina Linnaeus, 1758: 815.
Bugula neritina, Oken, 1815: 89.
Bugula neritina, Robertson, 1905: 266.
Bugula neritina, Waters, 1909: 135.
Bugula neritina, Marcus, 1937, 67.
Bugula neritina, Hastings, 1943: 430.
Bugula neritina, Osburn, 1947: 22.
Bugula neritina, Maturo, 1957: 42.
Bugula neritina, Ryland, 1960: 74.
Bugula neritina, Ryland, 1965: 45.
Bugula neritina, Maturo, 1966: 560.

Colonias erectas, ramificadas, formando densas matas con aspecto de algas, de hasta 10 cm aproximadamente de alto, de color pardo-rojizo o púrpura; bifurcaciones de tipo 4 y 5. Ramas formadas por dos series longitudinales de zooides, alternados, más angostos en su parte proximal y con el extremo distal trunco; la membrana frontal se extiende a lo largo de casi toda la superficie frontal. Sin espinas ni avicularias; el ángulo distal externo puede proyectarse ligeramente. Ovicelas grandes, globulares, adheridas al ángulo distal interno del zooecio, orientadas oblicuamente al eje de la rama, con abertura no visible. Polipidio con 23-24 tentáculos. Ancéstrula de aspecto similar al zooecio adulto, sin espinas ni prolongaciones.

OBSERVACIONES

Esta especie constituye uno de los organismos más representativos de las comunidades incrustantes de Puerto Belgrano. Por sus características distintivas (color, ausencia de espinas y avicularias, forma y posición de las ovicelas) es de fácil y rápida identificación. Su presencia en el puerto de Mar del Plata ha sido ocasional y siempre a través de ejemplares de muy pequeño talla; no ha sido registrada hasta el momento en Puerto Quequén.

En Puerto Belgrano, *Bugula neritina* es una especie muy abundante y de fijación anual, con un período de mayor intensidad en la colonización entre diciembre y marzo, coincidente con la época cálida. En esta época presenta un cremiento muy acelerado; los ejemplares pueden llegar a tallas de 65 mm en períodos de treinta días e incluso alcanzan la madurez sexual en lapsos más breves.

Este briozoo puede integrarse a las comunidades incrustantes durante las primeras etapas sucesionales, fijándose en estos casos directamente sobre el sustrato experimental. En comunidades bien desarrolladas se le encuentra sobre tunicados (*Ciona intestinalis, Botryllus schlosseri,* Didemnidae), sobre otros briozoos (*Cryptosula pallasiana, Conopeum reticulum, Alcyonidium polyoum*) y cirripedios (*Balanus amphitrite*). A su vez, constituye una adecuada superficie de asentamiento para la fijación de numerosos organismos; por tal motivo, las colonias más viejas se encuentran a menudo densamente cubiertas de epibiontes.

Para aguas argentinas existe una cita de esta especie, correspondiente a islas Malvinas (Hastings, 1943); la presente es la primera cita en trabajos de índole sistemática para el sector continental del país. Anteriormente, su límite de distribución austral en el Atlántico occidental correspondía a Brasil (Marcus, 1937).

Bugula flabellata (Thompson, 1847)
(fig. 7)

Avicularia flabellata Thompson, 1847: 106.
Bugula flabellata, Hincks, 1880: 80.
Bugula flabellata, Robertson, 1905: 270.
Bugula flabellata, Marcus, 1938.
Bugula flabellata, Osburn, 1947: 23.
Bugula flabellata, Ryland, 1960: 82.
Bugula flabellata, Ryland, 1965: 42.

Colonias erectas, ramificadas, de color blanco, marfil o anaranjado claro; ramas flabeliformes, más anchas distalmente; crecimiento algo espiralado. Zooides en series de tres-ocho, alargados, aproximadamente del mismo ancho en todo su largo; la membrana frontal ocupa casi toda la superficie frontal; el ángulo distal externo de los zooecios de la serie marginal lleva tres espinas; todos los ángulos distales internos llevan dos espinas; el tamaño de las espinas varía considerablemente; las de los ángulos externos de los zooecios marginales pueden ser muy grandes. Avicularias con pico fuertemente curvado hacia abajo, presentes en los zooecios de la serie marginal y en los de las series internas; las primeras son considerablemente más grandes que las últimas; se ubican sobre le margen lateral del zooecio, a un tercio o un medio de distancia desde el borde superior de la membrana frontal. Ovicelas subglobulares, con abertura moderadamente amplia. Polipidio con 14 tentáculos. Ancéstrula típicamente con tres espinas proximales y tres en cada ángulo distal; se han observado variaciones en el número de espinas distales, pero siempre están presentes las tres proximales (una mediana y dos laterales).

OBSERVACIONES

Es una especie que aparece frecuentemente en las muestras de Puerto Belgrano, si bien siempre en pocas cantidades. En el puerto de Mar del Plata se la registra en forma ocasional y generalmente enmascarada por las abundantes colonias de *Bugula stolonifera;* en años anteriores, *Bugula flabellata* resultaba una especie más frecuente en esta zona. En Puerto Quequén no ha sido registrada la presencia de este briozoo.

Bugula flabellata no había sido citada previamente para Argentina. En el Atlántico occidental, el límite de distribución austral correspondía a Brasil (Marcus, 1938).

Bugula simplex Hincks, 1886
(figs. 8 y 17)

Bugula simplex, Hincks, 1886: 265.
Bugula flabellata, Osburn, 1912: 225.
Bugula flabellata. Rogick y Croasdale, 1949.
Bugula simplex, Ryland, 1960: 91.
Bugula simplex, Ryland, 1965: 49.

Colonias de 1,4 a 3 cm de alto aproximadamente, ramificadas, de color pardo-anaranjado o amarillento; ramas estrechas en el origen, ensanchándose distalmente. Zooecios en series de tres-seis, más angostos en la zona proximal; la membrana frontal ocupa casi toda la superficie frontal; el zooecio lleva una espina en cada ángulo distal; muy raramente, dos; los zooecios marginales pueden presentar 2:1 espinas; el desarrollo de las espinas es muy variable, pudiendo estar en algunos casos muy desarrolladas y en otros fuertemente reducidas. Avicularias presentes sólo en los zooecios de la serie marginal, adheridas al margen externo a un cuarto de distancia del borde superior del zooecio, con pico suavemente curvado hacia abajo. Ovicelas aproximadamente hemiesféricas. Polipidio con 13-14 tentáculos. Ancéstrula con una espina mediana y dos en cada ángulo distal, con tres estolones cortos y chatos.

OBSERVACIONES

Es una especie muy poco frecuente en las comunidades incrustantes locales y que a simple vista puede ser confundida con *Bugula flabellata.* Un análisis más detallado, sin embargo, permite separar ambas especies sin inconvenientes, ya que presentan características bien distintivas (número de espinas, posición y forma de avicularias, forma de las ovicelas). Hasta el presente, esta especie sólo ha sido hallada en Puerto Belgrano y en forma ocasional.

Bugula simplex no había sido citada previamente para Argentina y el presente hallazgo amplía notablemente su distribución, cuyo límite sur correspondía a la zona del Caribe (Ryland, 1965).

Bugula stolonifera Ryland, 1960
(fig. 9)

Bugula californica, Marcus, 1937: 71.
Bugula californica, Maturo, 1957: 45.
Bugula stolonifera, Ryland, 1960: 78.
Bugula stolonifera, Ryland, 1965: 50.
Bugula stolonifera, Maturo, 1966: 568.

Colonias erectas, ramificadas, de 3-5 cm de alto aproximadamente, formando densas matas, de color amarillo-grisáceo o amarillo-verdoso; los estolones primarios que salen de la ancéstrula pueden extenderse sobre el sustrato, dando origen cada tanto a colonias secundarias. Zooides dispuestos en series de dos; ramas con bifurcaciones de tipo 4, ocasionalmente de tipo 3 en algunas porciones de la colonia o de tipo 5 en las zonas más distales. Zooecios largos y estrechos, más angostos en su base; la membrana frontal ocupa un medio a un tercio de la superfice frontal; el ángulo distal externo del zooecio lleva dos espinas; el interno, una; las espinas son tubulares, bien calcificadas y generalmente bien desarrolladas; el zooide «E» de la bifurcación tipo 4 puede presentar 1:1 espinas y ocasionalmente algunos zooides involucrados en la bifurcación pueden presentar 2:2 espinas. Avicularias adheridas al margen externo del zooecio, a un cuarto o un medio de distancia desde el borde superior de la membrana frontal, de perfil redondeado y pico corto, curvado suavemente hacia abajo; de acuerdo a su tamaño, las avicularias pueden ser agrupadas en tres clases (Maturo, 1966):

- Pequeñas (0,08-0,11 mm), situadas en los zooides «E» de la bifurcación tipo 4; a menudo están ausentes.

- Medianas (0,14-0,17 mm), situadas generalmente en zooides que forman el ángulo interno de la bifurcación y en zooides próximos al mismo.
- Grandes (0,18-0,24 mm), que pueden exceder el ancho del zooecio.

Ovicelas subglobulares, altas, con abertura conspicua. Ancéstrula con una espina mediana y tres en cada ángulo distal; a veces también se observan dos espinas en cada ángulo distal; en este caso, la ancéstrula puede presentar similitud con la de *Bugula simplex.*

OBSERVACIONES

Bugula stolonifera es el briozoo más importante de las comunidades incrustantes del puerto de Mar del Plata, llegando a ser uno de los organismos dominantes durante ciertas etapas sucesionales de las mismas. En la zona de Puerto Belgrano, a pesar de estar bastante bien representado, es superado ampliamente por *Bugula neritina;* no ha sido registrado hasta el momento en Puerto Quequén.

En el puerto de Mar del Plata es una especie de fijación estacional, con un período principal que se extiende aproximadamente entre noviembre y mayo, coincidente con el incremento de temperatura del agua. Durante las épocas de mayor abundancia, las colonias constituyen un espeso tapiz que cubre el sustrato experimental; entre ellas suele acumularse abundante detritus y encuentran refugio otros organismos colonizadores (*Corophium insidiosum, Polydora ligni, Bowerbankia gracilis*). También pueden encontrarse colonias jóvenes de *Bugula stolonifera* sobre *Balanus amphitrite, Ciona intestinalis*, Serpulidae, Campanulariidae, etc.

En Puerto Belgrano esta especie presenta un ciclo de fijación más restringido que *Bugula neritina* y que se extiende aproximadamente entre noviembre y mayo, semejante a lo observado en Mar del Plata. Suele encontrársela adherida directamente sobre los sustratos experimentales, como así también sobre otros organismos de la comunidad (*Ciona intestinalis, Cryptosula pallasiana, Conopeum reticulum, Botryllus schlosseri, Balanus amphitrite,* etc.).

Bugula stolonifera no había sido citada previamente para Argentina. El límite de distribución austral en el Atlántico occidental correspondía probablemente a Brasil, ya que, según Maturo (1966), parte del material descrito por Marcus (1937) como *Bugula californica* sería, en realidad, *Bugula stolonifera.*

CLAVE PARCIAL PARA LAS ESPECIES DE *BUGULA*

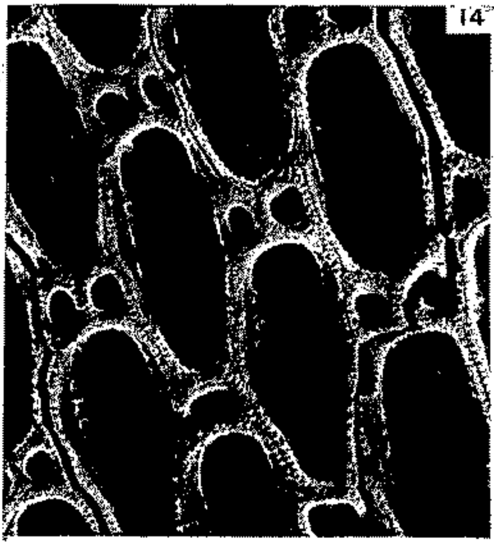
1.	Sin avicularias. Colonias de color rojizo o pardo rojizo	*B. neritina*
—.	Avicularias presentes. Colonias de colores claros (blancas, amarillentas, grisáceas o anaranjadas)	2
2.	Ramas compuestas por series de dos zooides, largos y delgados. Angulo distal externo del zooecio con dos espinas, el interno con una espina	*B. stolonifera*
—.	Ramas compuestas por series de más de dos zooides (generalmente de 3-8).	3
3.	Cada ángulo distal externo típicamente con una espina, raramente con dos espinas. Avicularias sólo en la serie marginal de zooides. Ramas generalmente compuestas por series de tres a seis zooides	*B. simplex*
—.	Angulo distal externo con tres espinas en los zooides marginales, todos los internos con dos. Avicularias con pico fuertemente curvado, presentes tanto en la serie marginal de zooides como en las internas. Ramas generalmente compuestas por series de tres a ocho zooides	*B. flabellata*

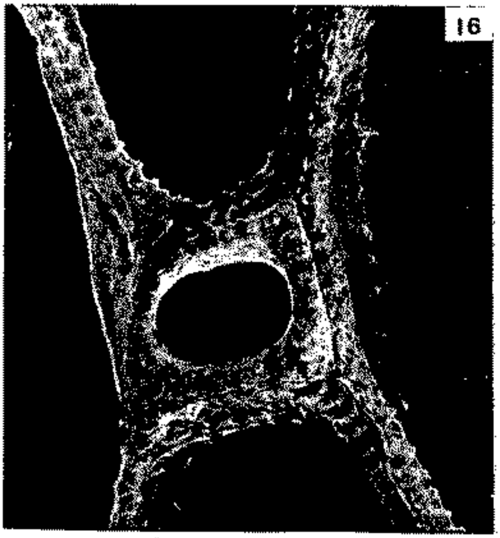
— Suborden Ascophora Levinsen, 1909.
— Familia Cheiloporinidae Bassler, 1936.
— Género *Cryptosula* Canu y Bassler, 1925.

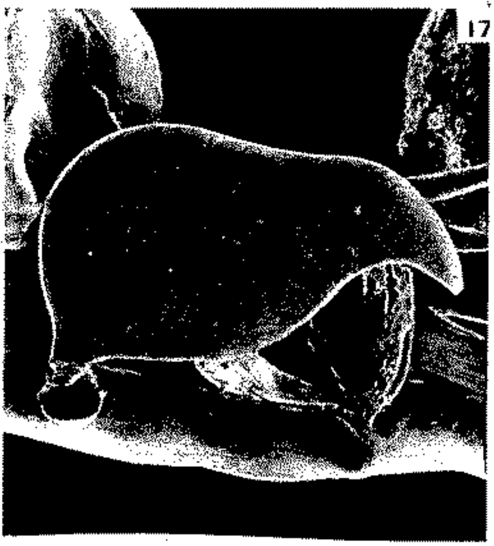
Cryptosula pallasiana (Moll, 1803)
(figs. 18-23)

Eschara pallasiana Moll, 1803: 57.
Lepralia pallasiana, Osburn, 1912: 240.
Cryptosula pallasiana, Marcus, 1942: 58.
Cryptosula pallasiana, Rogick y Croasdale, 1949: 55.
Cryptosula pallasiana, Maturo, 1957: 58.
Croptosula pallasiana, Ryland, 1965: 71.

Colonias incrustantes, de color rosado, amarillento o anaranjado, a veces también blanco. Zooecios de forma hexagonal, alargada, a ve-





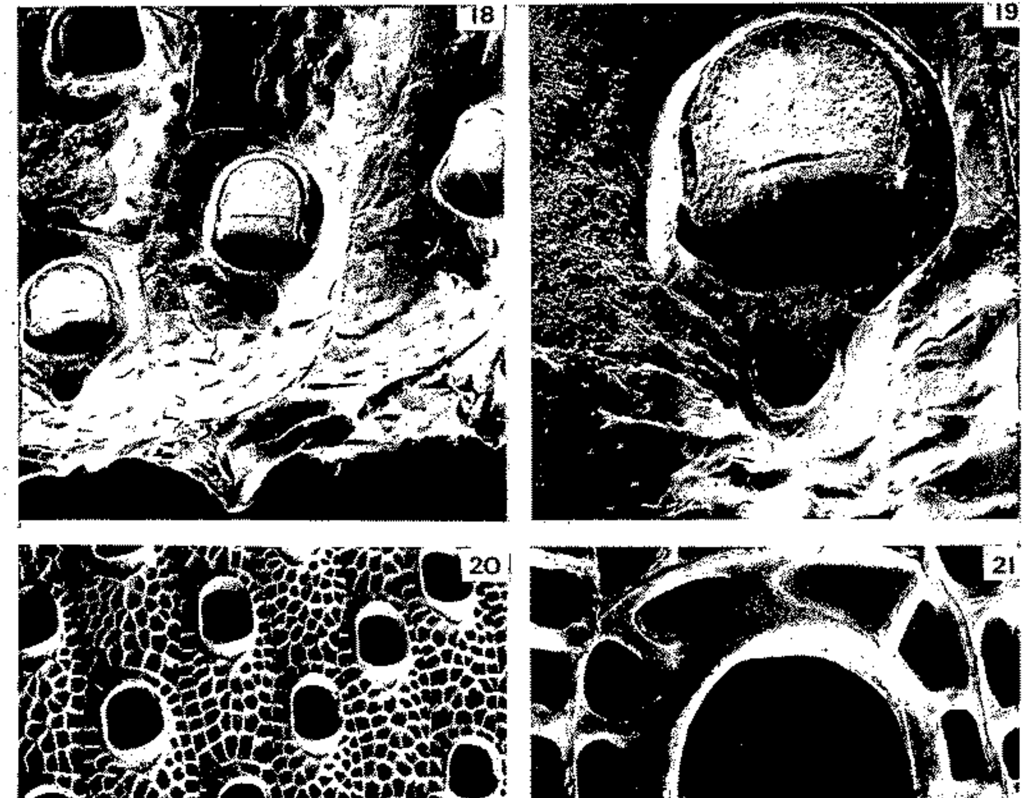


Figs. 14, 15 y 16.—*Conopeum reticulum*, previamente tratado con hipoclorito de NaOCl. 14. Aspecto general de la colonia. 15. Detalle de cavidades del extremo proximal del zooecio. 16. Detalle de cavidad proximal única.
Fig. 17.—*Bugula simplex*. Detalle de avicularia.

ces casi cuadrangular, moderadamente grandes (aproximadamente 0,60-0,70 mm de largo y 0,40 mm de ancho). Orificio en forma de campana, cardelas pequeñas; el peristoma es relativamente elevado y no fusionado a la frontal; la frontal es un tremocisto con grandes poros deprimidos. Sin ovicelas. A veces se observa una pequeña avicularia de mandíbula redondeada, justo por debajo del orificio. Ancéstrula similar a un zooecio adulto, pero con menos poros.

OBSERVACIONES

Junto con *Conopeum reticulum* es el briozoo incrustante más importante de la zona



FIGS. 18, 19, 20 y 21.—*Cryptosula pallasiana*. 18. Aspecto general de una colonia con avicularias. 19. Detalle de un individuo con avicularia. 20. Aspecto general de una colonia, previamente tratada con NaOCl. 21. Detalle de orificio, previamente tratado con NaOCl.

de Puerto Belgrano. También se le encuentra en Puerto Quequén y en el puerto de Mar del Plata. En este último es actualmente una especie poco significativa y de fijación ocasional; durante los primeros ensayos en la zona se le registraba en forma más abundante. Cabe mencionar que, a diferencia de otras especies mencionadas, *Cryptosula pallasiana* es bastante frecuente en las zonas naturales aledañas.

El ciclo de fijación de esta especie en Puerto Belgrano puede extenderse a lo largo de todo el año, pero presenta un período de colonización más importante entre octubre y abril. En Puerto Quequén, el período de fijación es más breve y coincide con el de mayor intensidad de Puerto Belgrano.

Al igual que *Conopeum reticulum*, las colonias jóvenes que logran desarrollarse sobre sustratos libres son de forma circular y totalmente adheridas. La falta de espacio puede traer aparejado un crecimiento de tipo erguido en ciertas porciones de la colonia; distintas colonias pueden asimismo unirse por sus bases, separándose del sustrato a modo de pequeñas hojas bilaminares. En comunidades bien desarrolladas este briozoo crece también sobre *Ciona intestinalis*, *Bugula neritina*, *Botryllus schlosseri*, *Balanus amphitrite*, etc., llegando a cubrirlos totalmente. En épocas de gran desarrollo, en que *Cryptosula pallasiana* se extiende ampliamente sobre los sustratos experimentales, constituye a su vez una superficie de asentamiento para otros organismos colonizadores.

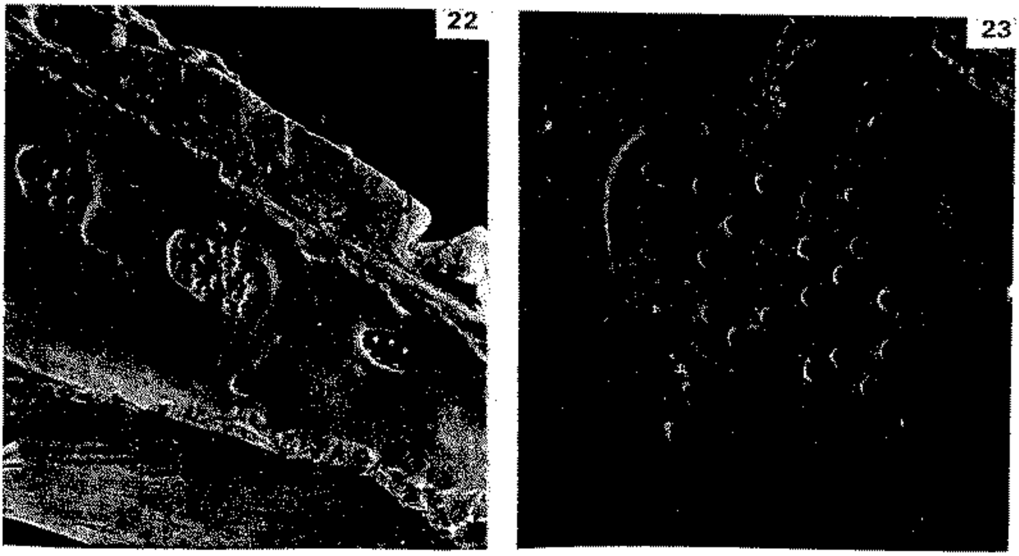
Esta especie no había sido citada previamente para Argentina en trabajos de índole sistemática. Su límite de distribución austral en el Atlántico occidental correspondía anteriormente a Brasil (Marcus, 1942).

— Clase STENOLAEMATA Borg, 1926.
— Orden CYCLOSTOMATA Busk, 1852.
— Suborden ARTICULATA Busk, 1859.
— Superfamilia ARTICULOIDEA Busk, 1859.
— Familia CRISIIDAE Johnston, 1838.
— Género *Crisia* Lamouroux, 1812.

Crisia eburnea (Linnaeus, 1758)

Sertularia eburnea Linnaeus, 1758: 810.
Crisia eburnea, Osburn, 1912: 215.
Crisia eburnea, Borg, 1944: 158.
Crisia eburnea, Maturo, 1957: 30.

Colonias erectas y articuladas, de color blanco, las ramas levemente curvadas hacia adentro en su extremo distal. Gonozooide alargado,



FIGS. 22 y 23.—*Cryptosula pallasiana*. 22. Detalle de la pared lateral de un zooecio, mostrando placas multiporosas. 23. Detalle de una placa multiporosa.

muy ensanchado distalmente; ooeciostoma pequeño, curvado hacia adelante, con orificio elíptico alargado transversalmente; generalmente reemplaza al segundo o tercer zooide del internudo fértil. Internudos típicamente con cinco-siete zooecios tubulares, casi totalmente fusionados entre sí, excepto en sus extremos distales, dispuestos en forma alternada. Articulaciones de color amarillento a pardo, siendo más oscuras en porciones más viejas de la colonia.

OBSERVACIONES

El único material coleccionado proviene de la zona de Puerto Belgrano y, además de ser muy escaso, no presentaba gonozooides. Los caracteres analizados responden a la descripción de *Crisia eburnea*, pero esto deberá ser confirmado mediante la observación de ejemplares fértiles.

Crisia eburnea ha sido citada para la zona de Tierra del Fuego (Borg, 1944); en la provincia de Buenos Aires, su presencia no había sido registrada previamente.

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Este trabajo ha sido subsidiado en parte por la S.E.C.Y.T. (Leg. 8451/78; Res. 489/78).

GLOSARIO

Ancéstrula.—Primer zooide de la colonia; surge a partir de una larva producida sexualmente, fijada, y posteriormente metamorfoseada; de ella se origina el resto de la colonia por reproducción asexual; su aspecto es, por lo general, diferente del de un zooide adulto y es característico de cada especie.

Avicularia.—Organo característico de los integrantes del orden Cheilostomata; puede ser sésil *(Cryptosula)* o pedunculada *(Bugula)*, en cuyo caso presenta una forma típica de cabeza de pájaro; se trata de zooides modificados en los cuales el opérculo está altamente desarrollado (mandíbula) y el polipidio reducido.

Bifurcación.—Ver zooide A-H.

Cardelas.—Apófisis que se encuentran ubicadas una a cada lado del orificio, que actúan como gozne y por las cuales está suspendido el opérculo.

Criptocisto.—Lámina calcárea de forma y desarrollo variables, que se origina en las paredes del zooecio y está situada por dentro de la membrana frontal.

Estolón.—Parte rastrera de las colonias, formada por zooides altamente modificados, típica en los Ctenostomata.

Frontal (superficie frontal).—Pared del zooecio en la cual se sitúa el orificio.

Gimnocisto.—Conjunto de las paredes frontales calcáreas, exteriores a la membrana frontal.

Gonozooide.—Cámara de incubación de los Cyclostomata; es un zooide modificado y especializado, de mayor volumen que el resto de los zooides.

Internudo.—Cada una de las porciones de la colonia comprendida entre dos articulaciones sucesivas en los Cyclostomata.

Membrana frontal.—Lámina flexible que cubre el opesio en los Cheilostomata Anasca.

Ooeciostoma.—Porción distal del gonozooide de los Cyclostomata, generalmente de forma tubular, anterior al orificio de salida.

Opérculo.—Tapa quitinosa, a veces membranosa o considerablemente reforzada, que cierra el orificio de los Cheilostomata.

Opesio.—Area de la superficie frontal del zooecio no calificada, limitada por las paredes calcáreas (gimnocisto) en los Cheilostomata Anasca.

Ovicela.—Cámara incubatriz externa, típicamente en forma de capucha y ubicada en la parte superior del zooide fértil, en la cual se desarrollan los embriones de los Cheilostomata.

Peristoma.—Tubo más o menos elevado que rodea el orificio primario de los Cheilostomata Ascophora.

Polipidio.—Partes internas vivas de cada individuo; consta esencialmente de una corona de tentáculos (lofóforo), el tubo digestivo en forma de U y las porciones correspondientes al sistema nervioso, sistema muscular, etc.

Tremocisto.—Capa calcárea más externa de la pared frontal de los Cheilostomata Ascophora, generalmente muy porosa.

Zooecio.—Cubierta externa de cada uno de los individuos de la colonia.

Zooide.—Cada uno de los individuos de la colonia; comprende una parte viva (polipidio) y la correspondiente cubierta externa no viva (zooecio).

Zooide A-H.—En las especies biseriadas, designación de los zooides que forman una bifurcación (Harmer, 1926); de acuerdo a la forma de ramificación de la colonia, las bifurcaciones se clasifican en tres tipos, 3, 4 y 5 (Harmer, *op. cit.*).

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BIOCHEMICAL ANALYSIS OF THE RESPONSE OF THE MARINE MICROFOULING COMMUNITY STRUCTURE TO CLEANING PROCEDURES DESIGNED TO INCREASE HEAT TRANSFER EFFICIENCY

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SUMMARY

The microfouling community that develops on aluminum pipes from rapidly flowing sea water is markedly affected by the mechanical cleaning procedures required to maintain the efficient heat transfer properties necessary in the condenser system of the Ocean Thermal Energy Conversion system.

Sensitive measures of the microbial biomass, such as the extractable lipid phosphate, the extractable palmitic acid and the total organic carbon show good correlation with the heat transfer efficiency (R_f) in the early stages of free fouling. After mechanical cleaning with either manually operated brushes or the MAN system, measures of the total biomass such as total organic carbon show reasonable correlation to the R_f. After cleaning, measures of cellular biomass such as lipid phosphate or lipid palmitic acid *do not correlate* with the R_f and the ratios of total organic carbon.

Mechanical cleaning changes the community structure of the microbes. The morphology of the population by scanning electron microscopy (SEM) shows selective removal of the larger and morphologically more complex microeukaryotes with retention of a community enriched in bacteria. Examination of the fatty acid composition of the community shows cleaning-induced selectivity not only for the bacterial prokaryotes but for a specific proportion of the bacteria. A population difference between the bacteria retained after manual brushing and continuous brushing with the MAN system can also be demonstrated.

The SEM morphology, the relationship between R_f and measures of total and cellular biomass, the increase in the ratio of total organic carbon to cellular biomass and the steady increase in a microbial population enriched in linoleic acid all point to an accumulation of extracellular biopolymer with the cleaning procedures. With intermittent cleaning the exopolymer accumulation enhances the colonization by the microeukaryotes between the cleaning cycles.

1. INTRODUCTION

The practical utilization of the enormous solar energy available in the Ocean Thermal Energy Conversion (OTEC) system requires extremely efficient heat transfer to utilize the small temperature gradient available. For this system to be cost effective the fouling resistance to heat transfer (R_f) must be held to such low levels that cleaning counter measures must be utilized (1) *. To best apply effective countermeasures the physiochemical properties and biological succession of the microfouling film must be examined.

This paper presents a report of methods

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developed to measure the relationship between the biomass and community structure of the microfouling film as the succession is influenced by mechanical cleaning in simulated OTEC condenser tubes.

The relative proportions of the fatty acids from the lipids extracted from the microfouling organisms will be compared to the morphology in scanning electron micrographs (SEM). The reliability of this type of analysis in differentiating the prokaryote (bacterial and cyanophyte) and microeukaryote (microscopic uni and multicellular animals, plants and fungi) community structure has been demonstrated (2). Biochemical measures of the estuarine detrital microbes correlated with the expected response induced by antibiotics and paralleled SEM morphology. Extractable lipid phosphate as a measure of the cellular biomass has been shown to correlate with the adenosine nucleotides, muramic acid and rates of lipid and DNA synthesis (3, 4).

Previous work with various surfaces exposed to marine environments has established that a primary organic film facilitates the attraction and attachment of the fouling microbes (5-8). These microbes become increasingly attached to the surface, generate an external polymer, which in turn attracts a diverse microeukaryote fouling population (9-11). Evidence presented in this study shows the formation of an extracellular polymer both increases the R_f and stimulates the development of a diverse microfouling community.

2. MATERIALS AND METHODS

OTEC SIMULATION SYSTEM

The OTEC simulation system employed 5054 aluminum pipes 2.1 cm in diameter through which sea water flowed at a rate of 6 ft/sec. The device for measuring the film side heat transfer coefficient and the flow driven MAN brushing system has been described (12). In the free fouling experiments the pipes were cleaned manually with a stiff bristle nylon bottle brush as indicated in figure 1. Samples consisting of duplicate 29 cm pipe sections (from the free fouling pipes) or 8.5 cm sections from the MAN brushing system were cut from the flowing stream and quick frozen in dry ice. At the time of removal, prescored coupons were removed and fixed for scanning electron microscopy in 0.4 % V/V glutaraldehyde in filtered sea water. During the test period (September 19 to November 2, 1979) the sea water showed the following properties: conductivity, 42-44 mmhos/cm; salinity,

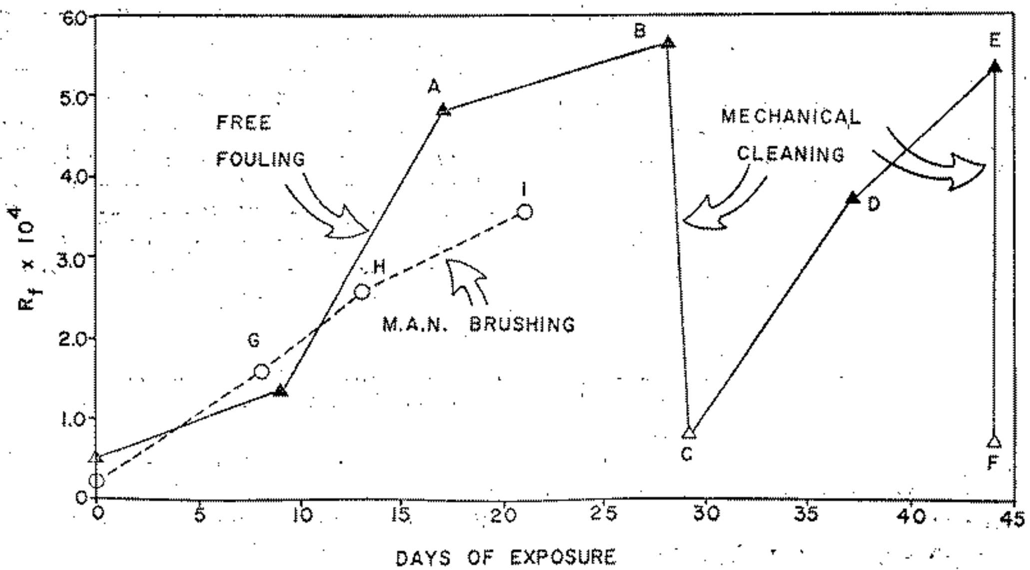

FIG. 1

77 ⁰/₀₀; temperature, 21-28° C; pH, 7.6-7.9; dissolved oxygen, 4.7-6.9 ppm; biochemical oxygen demand, 2.1-3.4 ppm; total organic carbon, 520-620 mg/l; ammonia, 0.005-0.01 mg/l; nitrate, 0.002-0.004 mg/l; and phosphate 0.03-0.04 mg/l.

Scanning Electron Microscope (SEM)

Coupons with the fixed microbial film were dehydrated, critical point dried, shadowed and examined with the Cambridge Stereoscan S4-10 microscope as described (13).

Total Organic Carbon (TOC)

TOC was measured from pipe sections treated with phosphoric acid, purged with oxygen, sealed, combusted. The CO_2 was then measured with an Oceanography International Corporation non-dispersive infrared analyzer.

Extraction of the Lipids

Lipids were extracted after rewarming the frozen pipes to room temperature using the modified Bligh and Dyer procedure in the pipe which was sealed with teflon and stainless steel plugs as described (14). The lipids were recovered from the organic phase and subjected to acid methanolysis. The chloroform phase containing the lipids was fractionated chromatographically on thin layer plates. The fatty acid methyl esters were recovered and analyzed by gas liquid chromatography (2). The aqueous portion of the acid methanolyslate was digested and analyzed for phosphate colorimetrically (3).

Gas Liquid Chromatography

The fatty acid methyl esters dissolved in hexane were introduced without splitting using a 30 sec venting time with a model 8000 autosampler on to a 50 meter glass capillary column coated with Silar 10C in a Varian 3700 gas chromatograph. The oven temperature was programmed from 42 to 192° C with an isothermal period at 162° C and the final temperature as described (2). The helium carrier gas was at a flow rate of 1 ml/min. The detection was by flame ionization at 225° C. The autosampler delivered 2 µl with no carry over between samples. The identity of the major fatty acids was established by comparing their retention volumes to authentic standards, before and after hydrogenation, and to their fragmentation patterns with an electron impact-mass spectrometer (Bobibe and White, unpublished data).

Fatty Acid Nomenclature

The fatty acids are designated as the number of carbon atoms in the chain: the number of double bonds. With enoic esters the position of the ultimate double bond, i.e., the double bond closest to the ω end of the molecule, is designated as ω3, ω6, etc. Special structural designations are given as prefixes: a, i, Δ for anteiso, iso branching and cyclopropane structure respectively.

3. RESULTS

Effects of Microfouling on Heat Transfer Efficiency

Exposure of aluminum pipes to flowing sea water results in a loss of heat transfer efficiency (R_f) (Fig. 1). The rate of increase of this heat transfer resistance is depressed by continuous mechanical cleaning with the MAN brush system, however a continuous increase in heat transfer resistance is still observed. It requires 25 days of exposure to achieve a heat resistance greater than 5×10^{-4} hr ft² F°/BTU in the initial period of free fouling. After manual removal of the fouling with a stiff nylon brush it takes only 15 days to achieve the same level of heat transfer resistance (Figure 1, second cycle).

Relationship Between Resistance to Heat Transfer and Biofouling

In free fouling experiments with aluminum pipes at flow rates of 6 ft/sec, the extractable lipid phosphate from the microfouling community, the total palmitic acid (16:0) in the lipid and the total organic carbon show linear correlation with the R_f values (Table 1). The three measures of microfouling biomass also show good linear correlations between each other. However, when the microfouling community is subjected to continuous mechanical cleaning by the MAN brush system, the linearity between heat transfer resistance and biomass measures breaks down (Table 1).

The change in the relationship between the heat transfer resistance (R_f) and the biomass measure (total lipid, 16:0) with manual and MAN brush cleaning is illustrated in Figure 2.

The ratio of total organic carbon to 16:0 for the free fouling microflora is 66.2 (15.6) ($\bar{X} \pm$ SD) µg/nmole. This ratio for the MAN brushed microflora (taken at points G, H and I of figure 1), is 370 (147) ($\bar{X} \pm$ SD) µg/nmole which is significantly different at the 99 % level by t test from the ratio found in the free fouling communities. The ratio of TOC to 16:0 for the residue after manual cleaning (point C, figure 1) is 34.9 (2.8) ($\bar{X} \pm \pm$ SD) µg/nmoles which is significantly different at the 95 % level from the freely fouling community.

EFFECTS OF CLEANING ON THE MORPHOLOGY OF THE MICROFOULING COMMUNITY

Scanning electron microscopy shows a rich community with diverse morphology. This can be seen in figure 3, upper panel, in the preparation removed from OTEC simulation system at R_f 4.82 (point A, figure 1). With manual cleaning the gel-like corrosion layer is fragmented and a sparse community of small rods and filaments can be seen on the surface (figure 3, lower panel, corresponding to point C in figure 1). The MAN brushed samples at a similar R_f show the Vibrio-like bacterial microbes on the surface with occasional thin filaments (figure 3, middle panel). These

TABLE 1

RELATIONSHIPS BETWEEN HEAT TRANSFER RESISTANCE (R_f), EXTRACTABLE LIPID PHOSPHATE, TOTAL PALMITIC ACID, TOTAL ORGANIC CARBON AND

	LINEAR CORRELATION COEFFICIENTS	
	r	r^2
A. Free fouling		
R_f vs 16:0	0.96	0.91
R_f vs lipid PO_4	0.91	0.83
R_f vs T.O.C.	0.92	0.85
16:0 vs lipid PO_4	0.95	0.89
16:0 vs T.O.C.	0.91	0.83
Lipid PO_4 vs T.O.C.	0.82	0.67
B. M.A.N. brush cleaned		
R_f vs 16:0	— 0.36	0.13
R_f vs T.O.C.	0.60	0.36
16:0 vs T.O.C.	0.43	0.19

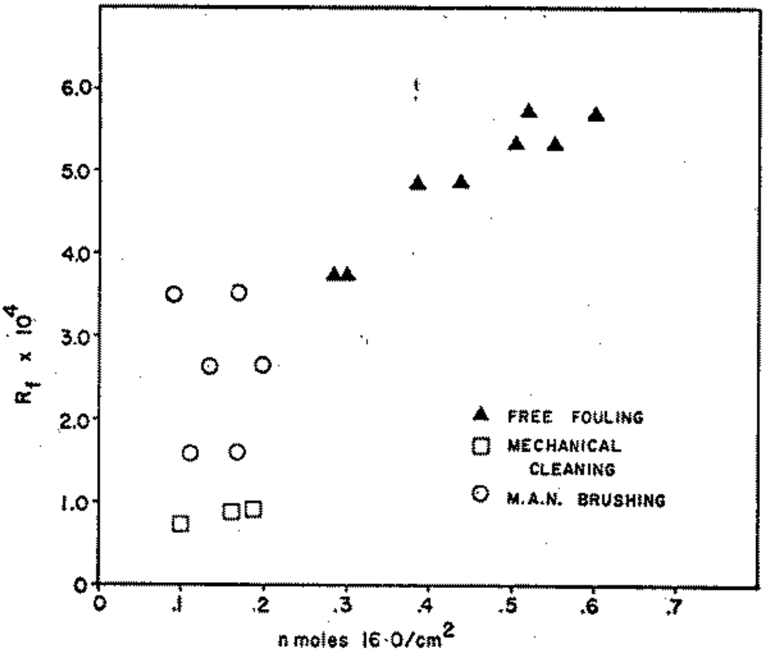
6.0
5.0
4.0
3.0
2.0
1.0
0
$R_f \times 10^4$
0
.1
.2
.3
.4
.5
.6
.7
n moles 16·0/cm²
FREE FOULING
MECHANICAL CLEANING
M.A.N. BRUSHING

FIG. 2

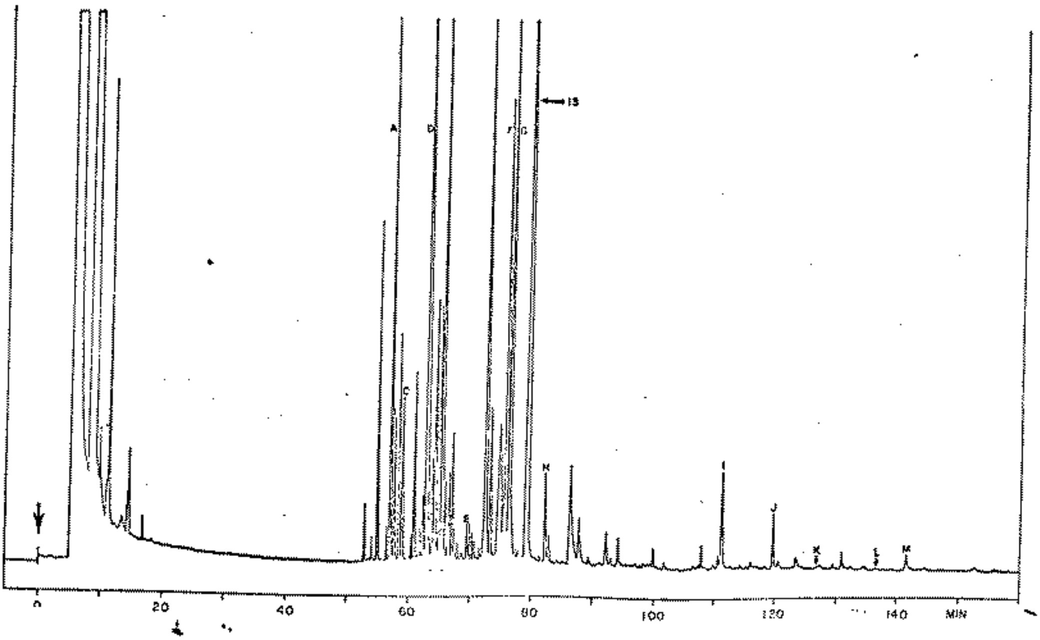
A
C
D
E
F
G
IS
H
I
J
K
L
M
0
20
40
60
80
100
120
140
MIN

FIG. 3

micrographs are taken from the sample labeled 1 in figure 1.

To examine the morphology of the microflora subjected to MAN brush cleaning, higher magnifications of the surface from the sample labeled G in figure 1 are illustrated in figure 4. The upper panel shows the relative uniformity of rod-shaped microbes. These are more clearly seen at higher magnifications in the middle panel. The filaments attaching these rods to the metal surface can be seen at the highest magnification (figure 4, lower panel).

FATTY ACID ANALYSIS OF THE MICROFOULING COMMUNITY

Separation of the aliphatic branched, cyclopropane and unsaturated fatty acids by glass capillary gas liquid chromatography derived from the lipids of the microfouling community is illustrated by the data in figure 5. The lipids were extracted from the microbes at point A (figure 1). The esters which previous studies have shown to be correlated with various components of the microbial assembly are indicated

TABLE 2

EFFECT OF CLEANING ON THE MICROFOULING COMMUNITY STRUCTURE

Sample [a]	CYCLE 1		CYCLE 2	
	A	B	C	D
$R_f \times 10^4$ [b]	4.82	5.67	0.83	3.75
Lipid phosphate [c]	2.80 (0.40)	3.50 (1.90)	0.30 (0.05)	1.70 (0.05)
Total organic carbon [d]	34.70 (1.00)	34.80 (1.70)	5.95 (0.98)	14.90 (0.23)
Total 16:0 [e]	0.41 (0.06)	0.55 (0.06)	0.17 (0.00)	0.29 (0.01)
a + i 15:0/16:0	4.30 (0.80)	2.60 (0.60)	0.50 (0.30)	2.20 (0.30)
Δ17:0/15:0	0.50 (0.30)	0.50 (0.10)	0.50 (0.00)	0.50 (0.20)
Δ17:0/16:0	0.04 (0.02)	0.03 (0.00)	0.03 (0.01)	0.05 (0.01)
18:1ω7/15:0	11.00 (3.00)	13.00 (1.90)	2.10 (0.70)	9.00 (5.60)
18:1ω7/16:0	0.80 (0.10)	0.70 (0.10)	0.13 (0.04)	0.80 (0.30)
18:1ω7/18:1ω9	3.30 (1.50)	3.80 (1.40)	0.20 (0.10)	2.90 (3.10)
18:2ω6/16:0	0.09 (0.03)	0.06 (0.00)	0.06 (0.04)	0.05 (0.01)
22:0/16:0	0.04 (0.01)	0.05 (0.01)	0.05 (0.01)	0.04 (0.02)
Total poly > 20/16:0	0.56 (0.50)	0.25 (0.15)	0.15 (0.15)	0.29 (0.18)

[a] Letters refer to points on Figure 1

[b] $R_f \times 10^4$ hr ft² F° per B.T.U.

[c] nmoles lipid phosphate per cm²

[d] μg carbon per cm²

[e] total 16:0 nmoles per cm²

in the chromatogram. The internal standard (19:0) is also indicated in figure 5.

CHANGES IN FATTY ACID COMPOSITION WITH CLEANING

The changes in the microbial biofouling fatty acid composition with free fouling and mechanical cleaning are illustrated in table 2. The data are given as ratios. The 16:0 represents the total microbial community, the 15:0 a large portion of the bacterial component of this community, and the 18:1ω9 (oleic acid) a large proportion of the prokaryotic and essentially all the microeukaryotic populations. The proportion of short branched fatty acids (a + i, 15:0) decreases five-fold with manual brushing. The populations containing these short branched fatty acids exist as higher proportions of the total biomass when the community is subjected to MAN brushing. The populations containing the bacterial cyclopropane fatty acid Δ17:0 slowly increase in

	CYCLE 3	M. A. N. BRUSH		
E	F	G	H	I
5.31	0.73	1.52	2.55	3.5
3.5 (0.10)	0.05 (0.00)	< 0.01	< 0.01	< 0.01
ND	ND	35.30 (1.70)	62.30 (23.30)	57.30 (1.00)
0.45 (0.70)	0.18 (0.24)	0.14 (0.04)	0.17 (0.05)	0.13 (0.06)
2.70 (0.10)	0.40 (0.10)	3.40 (0.10)	2.70 (0.40)	4.00 (0.80)
0.50 (0.10)	0.70 (0.00)	0.60 (0.10)	1.00 (0.50)	0.80 (0.10)
0.05 (0.01)	0.05 (0.00)	0.04 (0.01)	0.04 (0.02)	0.04 (0.01)
10.40 (0.20)	3.70 (3.40)	4.00 (0.30)	6.60 (1.50)	14.40 (8.20)
1.00 (0.20)	0.20 (0.10)	0.20 (0.00)	0.20 (0.05)	0.60 (0.30)
3.30 (0.10)	0.20 (0.10)	0.50 (0.20)	0.20 (0.10)	1.00 (0.00)
0.10 (0.02)	0.30 (0.30)	0.10 (0.07)	0.08 (0.03)	0.21 (0.02)
0.03 (0.01)	0.03 (0.00)	0.03 (0.01)	0.03 (0.01)	0.05 (0.01)
0.77 (0.09)	0.06 (0.05)	0.04 (0.01)	0.05 (0.03)	0.07 (0.04)

the residue left after manual brushing but do not increase in the MAN brushed community. The populations containing the anaerobic pathway of unsaturated fatty acid biosynthesis (resulting in 18:1ω7) are removed by manual cleaning and steadily increase in the MAN brushed community. When the bacterial populations containing 18:1ω7 are compared to therest to the prokaryotes and the microeukaryotes containing oleic acid (18:1ω9) the changes areless pronounced.

Linoleic acid (18:2ω6) is formed in microbes that seem to accumulate with both types of cleaning. The microbes containing long chain alkyl fatty acids (22:0) are not affected by cleaning procedures.

The most striking changes are detected in the microeukaryotes (algae, fungi, protozoa) which contain the polyenoic fatty acids longer than 20 carbon atoms. Both types of cleaning readily remove this population. There is very rapid recovery of this population in the second cycle after manual cleaning.

4. DISCUSSION

Cleaning countermeasures designed to maintain heat transfer efficiency markedly changed the composition of the microfouling community structure (fig. 3). Free fouling results in a morphologically diverse microbial film that is simplified with cleaning to a sparser community of narrow filaments and rods characteristic of bacteria. However, these morphological changes do not quantitatively describe the changes on heat transfer efficiency and provide no chemical insight into the dynamics of this film.

To understand the formation of this biofouling film in the OTEC rapid flow system, methods were developed that could provide information unbiased by selective assays requiring removal and growth of the organism yet were quantitative and not affected by the metallic surface. Analysis of lipids that could be extracted from the film represented a plausible measure of microbial biomass that could also provide insight into the community structure (14). Jeffries (15) utilized fatty acid analysis to characterize the fouling community on glass plates. Various bacteria are enriched in the a + i 15:0, 15:0 and Δ17 cyclopropane fatty acids. Some bacteria contain the unique anaerobic pathway for unsaturated fatty acid biosynthesis that yields cis vaccenic acid (18:1ω7) (15-18). Bacteria contain a significantly greater ratio of 15:0 to 16:0 than do other microorganisms (16, 18, 19). Since most of the bacterial monocultures examined contain at most one or two of these fatty acids, the ratio of a + i 15:0/15:0, Δ17:0/15:0, and 18:1ω7/15:0 can be used to monitor shifts in the bacterial community structure. Palmitic acid (16:0) is one of the major fatty acids in nearly all microorganisms (18, 19). Consequently the absolute amount of 16:0 can be used as a measure of cellular biomass and ratios of specific fatty acids to 16:0 can be an indication of that proportion of the film composed by various component populations. Linoleic acid (18:2ω6) is enriched in the lipids of cyanophytes (20), lower fungi (21), flexibacteria (22) and protozoa (23). Polyenoic fatty acids of chain length greater than 20 carbon atoms are found in microeukaryotes (23). Long alkyl chain fatty acids are rare in the eubacteria (17, 19).

In this study the free-fouling film shows morphological diversity in SEM that is reflected in the diversity of the fatty acids recovered from the cellular lipids (figure 3, table 2). Cleaning countermeasures depressed both the fatty acids characteristic of some of the bacteria and the microeukaryotes. This was expected from the changes in the SEM morphology. The impact of the cleaning is reflected in the fatty acids recovered from the residue film. Bacteria with lipids enriched in a + i 15:0 and 18:1ω7 are removed more effectively by the vigorous manual cleaning than the continuous MAN brushing system. The bacteria containing the cyclopropane fatty acids (Δ17:0) and the bacterial and microeukaryotic populations with lipids enriched in linoleic acid (18:2ω6) are the most resistant to removal by mechanical cleaning.

Biochemical analysis can be readily extended to other lipids as has been done in studies of the detrital and sedimentary microbes (2, 24). The formation of derivatives of steroids and hydroxy fatty acids that provide for electron capture detection with GLC or efficient fragmentation for detection by selective ion monitoring with gas chromatography-mass spectrometry should provide analyses with sufficient sensitivity to yield much more insight into the microfouling community.

Heat transfer efficiency correlates well with measures of the cellular biomass such as extractable lipid phosphate or total palmitic acid, as well as measures of the total biomass such as total organic carbon in the early stages of free fouling (table 1, figure 2). With cleaning countermeasures these relationships break down. The cellular biomass no longer correlates with heat transfer efficiency, although there is some correlation with total organic carbon (table 1). There is a 10 fold increase in the ratio of total to cellular biomass (TOC/16:0) with cleaning suggesting extra cellular products are forming larger proportions of the biofouling film with continued cleaning. Exopolymer hold-fasts can be readily detected in the high power scanning electron micrographs of mechanically cleaned surfaces (figure 4).

Much of the study of extracellular attachment polymers has involved attachment of bacteria to glass slides in sea water. Corpe showed the attachment film contained acidic polysaccharides which attracted diatoms and other bacteria (8, 9). The extracellular film retained after manual cleaning in the OTEC simulator was associated with an accelerated loss of heat transfer efficiency (figure 1) and rapid recruitment of a population with diverse fatty acids in the cellular lipids (table 2).

The formation of the extracellular hold-fast polymers by bacteria in sea water on glass slides can require protein synthesis (10) and the adhesion is released by proteolytic or amyeolytic enzymes or periodate treatment under specific conditions (10, 25). Extension of the biochemical analyses of the structure, formation and destruction of the extracellular adhesive polymers hopefully will provide more effective microfouling countermeasures.

ACKNOWLEDGMENTS

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PHYSICAL/CHEMICAL CHARACTERISTICS OF THE MACROMOLECULAR CONDITIONING FILM IN BIOLOGICAL FOULING

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INTRODUCTION

The process of biological fouling begins at the instant an engineering or structural material encounters a biological fluid. The sequence of events continues to a level of deposition that eventually impedes the movement of ships, destabilizes submerged oceanic structures, lessens heat exchange in cooling towers, restricts the passage of blood in native and artificial cardiovascular circuits, and promotes dental caries. This important sequence follows a universal order. Upon initial contact, a surface is modified by adsorbing biopolymers. Next, the attachment and proliferation of pioneer cells occurs which is followed by cellular or animal growth and finally mineralization. Although the nature of the biofouling process appears to be universal, the time for these events to occur varies with the concentration of biomass in the fluid. For example, the appearance of formed elements (i.e., bacteria or cells) on surfaces in the open ocean may take days, whereas in the blood stream platelets attach within minutes.

The severity of biofouling is dependent upon the macromolecular conformation that is predominant in the initial biopolymer layer. The exact nature of this conditioning layer is, however, unknown. In the maritime environment, the film is believed to be part of, or related to the humic acid or «gelbstoff» of the sea. From surface chemical measurements (1-6), this material has shown characteristics of being glycoproteinacious, anionic and highly hydrated. Microcalorimetric studies of the biofouling in blood (7, 8) have shown that the adsorption events are thermodynamically favored. The macromolecules may gain or lose freedom of movement upon adsorption, or may experience denaturation at the surface. Before these and other questions can be answered, further data need to be acquired.

EXPERIMENTAL APPROACHES

Research on primary fouling films can be approached experimentally from two basic directions: (a) *in situ* using the techniques fostered by the surface chemist, biophysicist, biochemist, immunologist and heat transfer engineer, or (b) removal of the film via scraping, ultra-sonic treatment, solvent attack, etc. We believe that the safest and most rewarding approach to be the former way, since in this manner the integrity and orientation of the adsorbed film are preserved.

We have successfully used the following surface chemical methodology in our biofouling investigations: internal reflection infrared spectroscopy, ellipsometry, surface potential measurement, contact angle determination, scanning electron microscopy, energy-dispersive x-ray analysis, and x-ray diffraction. These techniques, each informative themselves, provide a strong approach when used simultaneously. Germanium, shaped in the form of an internal reflection plate, provides a suitable substrate for the use of all of these techniques

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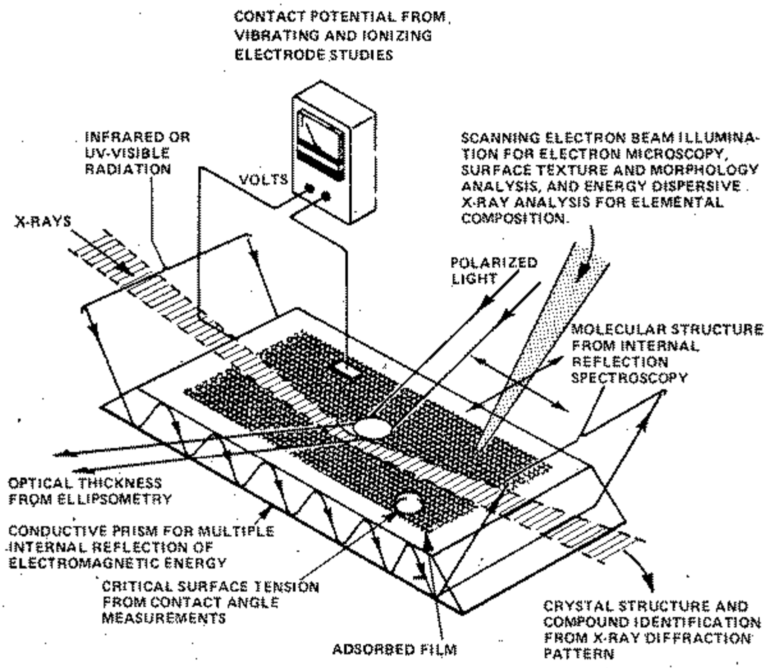


FIG. 1.—Schematic diagram of seven nondestructive methods which are applicable in turn to the same surface deposit, with sensitivity at the sub-microgram level.

(see Figure 1). In addition, germanium can be coated to simulate the surface chemistry of many engineering materials without the loss of any of its capabilities.

The mainstay of our chemical analyses is often surface spectroscopy using an internal reflection technique. Thicknesses and refractive indices of coatings and corrosion-resistant layers are estimated by ellipsometry. The electrical characteristics of films and substrates are determined with contact potential electrometers.

Internal reflection spectroscopy, making use of the optical path indicated in Figure 2, allows the recording of the diagnostic infrared «finger-print» for the most important interfacial layers of solids, liquids, and powders and of thin films without interfering signals from the bulk. The technique is sensitive enough to detect and identify films as thin as $\sim$ 20 Å, and follow changes in the composition, configuration and bonding within such films. The method is nondestructive, and so can be applied without reservation to delicate materials.

Ellipsometry, making use of an optical arrangement indicated in Figure 3, allows the rapid determination of the thickness and refractive index of films and coatings, with a sensitivity of a few Å. This technique also provides optical parameters for reflecting surfaces, and can monitor rapid changes in characteristics of substrates and films with little difficulty, in any environment, gaseous, liquid, or vacuum. The method is non-destructive.

Contact potential is determined with devices employing a widely used modification of the

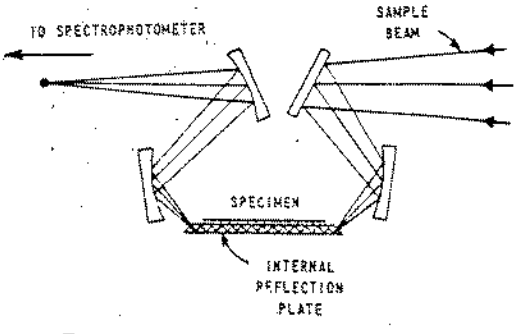


FIG. 2.—Internal reflection spectroscopy.

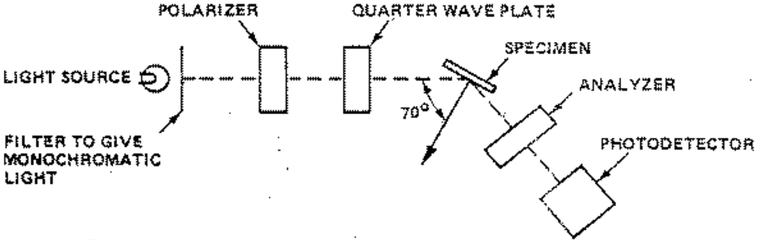


FIG. 3.— Schematic of the ellipsometer light path (Reference 6).

Kelvin method, wherein the difference of potential of two metals used as plates of a vibrating condenser is measured from the resulting alternating current flowing in an interconnecting resistor. In addition, an ionizing electrode-type device utilizing a null technique to measure the potential of the adsorbed film is also used.

Combination of these three powerful, nondestructive, and noncontacting measurement techniques provides a unique characterization of film composition, configuration, and organization, and changes therein, without altering the specimen preliminary to other studies.

An important requirement in much current research is for an extremely sensitive and reliable method of monitoring the surface properties of coatings and substrates. Perhaps the fastest and most sensitive technique known for identifying changes in surface constitution, of any material, is based upon contact angle measurements. Figure 4 is a simple diagram which defines the contact angle of a liquid on a solid surface. The angle is measured through the liquid phase so that a contact angle of zero degree ($\theta = 0°$) indicates that spontaneous spreading of the liquid takes place; larger equilibrium contact angles ($0° < \theta < 180°$) indicate poorer, or incomplete, surface wetting by the liquid phase.

Contact angle methods have been developed extensively over the past four decades by ZISMAN and coworkers at the Naval Research Laboratory. A large body of reliable data has been accumulated and a vast literature exists correlating contact angle data with surface properties of liquids and solids. A most useful parameter called the Critical Surface Tension, which is conceptually related to, but not necessarily equal to, the surface free energy of a material, has been defined from a graphical treatment of contact angle data. Figure 5 illustrates a model graph, called the ZISMAN plot. In a ZISMAN plot the cosines of the contact angles for a variety of pure liquids on a given solid are plotted against the liquid/

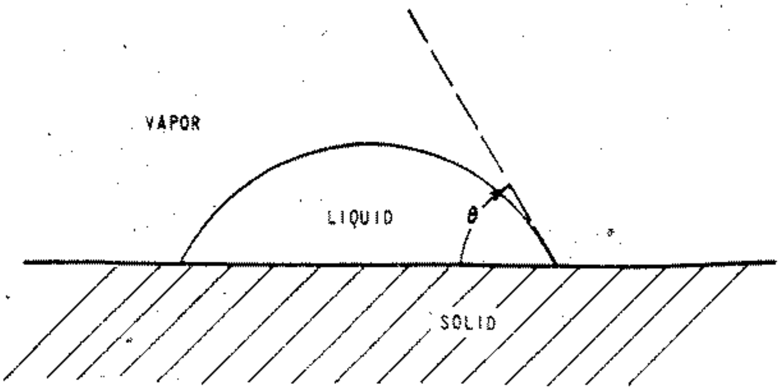


FIG. 4.—Definition of the contact angle Θ.

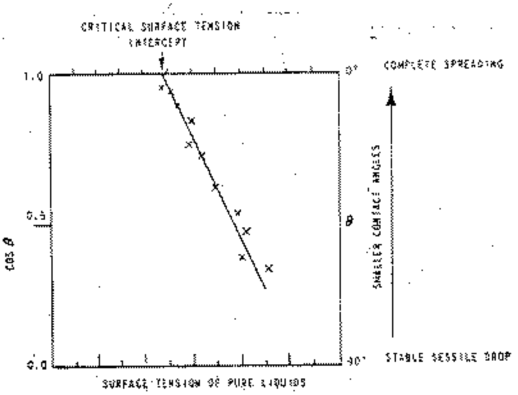


FIG. 5.—The Zisman plot.

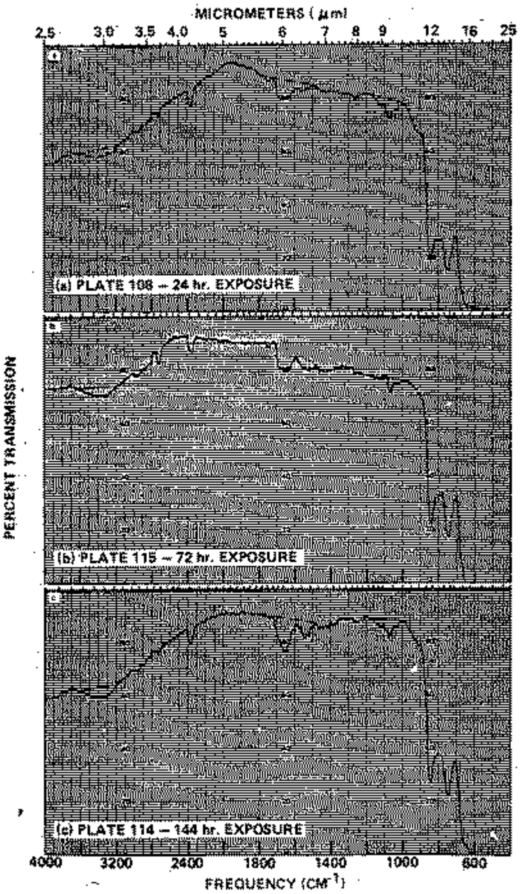


FIG. 6.—Internal reflection infrared spectra of adsorbed film on germanium internal reflection plates exposed to flowing sub-surface warm ocean water (Reference 2).

vapor surface tensions of the liquids. It has been learned empirically that a rectilinear fit to the data points is most often obtained. Since the intercept at the cos $\theta = 1$ axis is different for different surfaces, the intercept surface tension value is recorded as the Critical Surface Tension for the solid in question. Although this value is precisely defined only for a series of homologous liquids, it has been shown that liquids of all types generally fall along the same straight line or cluster closely around it in a narrow rectilinear band. The Critical Surface Tension intercept determined from a variety of pure liquids is thus an even more valuable parameter, since it characterizes the solid surface only, independent of the liquids used in its determination.

The most important consideration for our purposes is that the Critical Surface Tension values are intimately related to the surface constitution. Even small changes in the outermost atomic layer are reflected in a change of Critical Surface Tension, while other properties might remain essentially unchanged. For example, a simple hydrocarbon surface (like that of polyethylene) exhibits contact angles leading to a Critical Surface Tension of about 31 dynes/cm. Gradual replacement of hydrogen atoms in the surface by fluorine atoms gradually decreases the critical values to 19 dynes/cm (as observed with polytetrafluoroethylene). Conversely, gradual replacement of surface hydrogen with chlorine atoms leads to an increased Critical Surface Tension gradually approaching 41 dynes/cm (as with polyvinylchlorides).

It is apparent that contact angle methods —applied with care and interpreted by experienced workers—can provide rapid and inexpensive answers to questions of surface constitution and adhesion which must be addressed during research and development programs directed towards understanding and controlling interfacial phenomena.

REPRESENTATIVE BIOFOULING DATA

The sequence of internal reflection infrared spectra shown in Figure 6 typifies the results of adsorption experiments in the sea. These spectra show the enhancement of biomass on germanium after exposure to warm sub-surface water for 24, 72 and 144 hours, respectively. With time, the infrared absorption bands at approximately 3330, 1650 and 1550 cm^{-1} increase, indicating the proteinaceous character of the acquired film in the dry state. The broadness of the bands reflect its high hydration of hydroxylated state. (Note: The absorption bands at 2720 and 1080 cm^{-1} are instrumental grating changes, 2340 cm^{-1} reflect CO_2 absorption due to the imbalance in path length between sample and reference and 850, 750 and 650 cm^{-1} are attributed to the germanium.) After 24 hours of exposure, the surface was free of all gross deposits. Within 72 hours, many rod-shaped bacteria were seen and when examined after 144 hours, the test plates clearly showed the presence of many rod, flagellated and stalked bacteria.

The infrared signature of another example of the first biofouling layer is shown in Figure 7. After a mere ten minutes of contact with the fouling-prone water of Biscayne Bay, Florida (Fig. 7 A), the infrared spectra clearly indicate the adsorption of material that is protein-like. After 21 hours, the same absorption peaks broaden. The same experiment performed in an artificial seawater aquarium containing live and reproducing barnacles show a similar spectral picture after 22 hours. Additional exposure time resulted in further enhancement of the protein-bands as well as the appearance of a carbohydrate peak (at approximately 1050 cm^{-1} in Figures 7 D and 7 E).

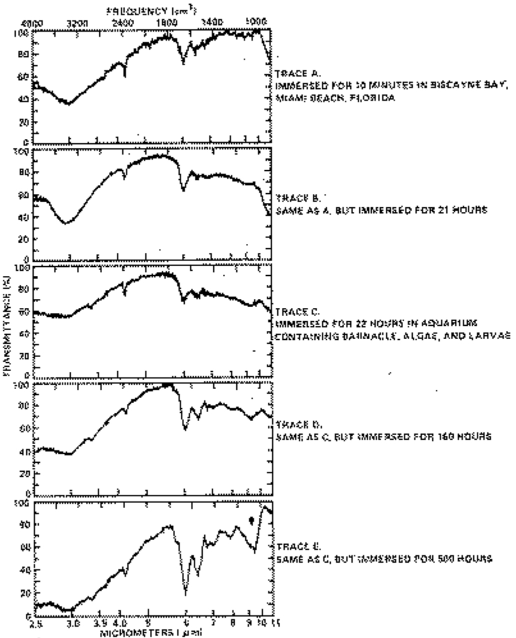


FIG. 7.—Characteristic infrared spectra of the spontaneously accumulated "conditioning" films on metallic slabs (germanium) immersed in fouling-prone seawater (Reference 5).

As mentioned above, the early events in biofouling are similar and independent of the biofluid nature. The thickness and the CST of the adsorbed films on germanium prisms exposed to the Gulf of Mexico water are compared to the fouling events for the blood protein fibrinogen in Figure 8. Note that seawater experiments occur over six days, whereas the blood protein data reflect adsorption within a period of one minute. In both studies, the *rate* of film thickness growth increases rapidly at the beginning, decreases significantly and then changes very little. Conversely, the wettability pattern of the absorbed film shows a decrease in the critical surface tension after a brief exposure followed by a very slight increase. The data suggest that the equilibrium film thickness for the adsorption process of this conditioning layer is reached rather early and that the biopolymer adsorbs in such a manner that its lower energy character is extended out into the fluid phase. In Table 1, the contact angle, ellipsometry and contact potential data for the prisms exposed to the Gulf of Mexico (144 hours) and fibrinogen (60 seconds) are compared. The low energy-low polarity nature of the collected films is confirmed by the γ^d and γ^p, the respective dispersive (i.e., nonpolar) and polar portions of the substrate's surface energy. These surface energy values are calculated from the contact angle data by the method of KAEBLE (9) and are additive to equal the composite surface energy. The surface chemical parameters for poly-γ-methyl-L-glutamate (PMG), a polypeptide whose secondary conformation under our experimental conditions was determined to be α-helical and the barium salt of stearic acid, barium stearate (BaSt), are also listed in Table 1 for comparative purposes. These latter two compounds were retrieved from the air/water interface of a Langmuir film balance,

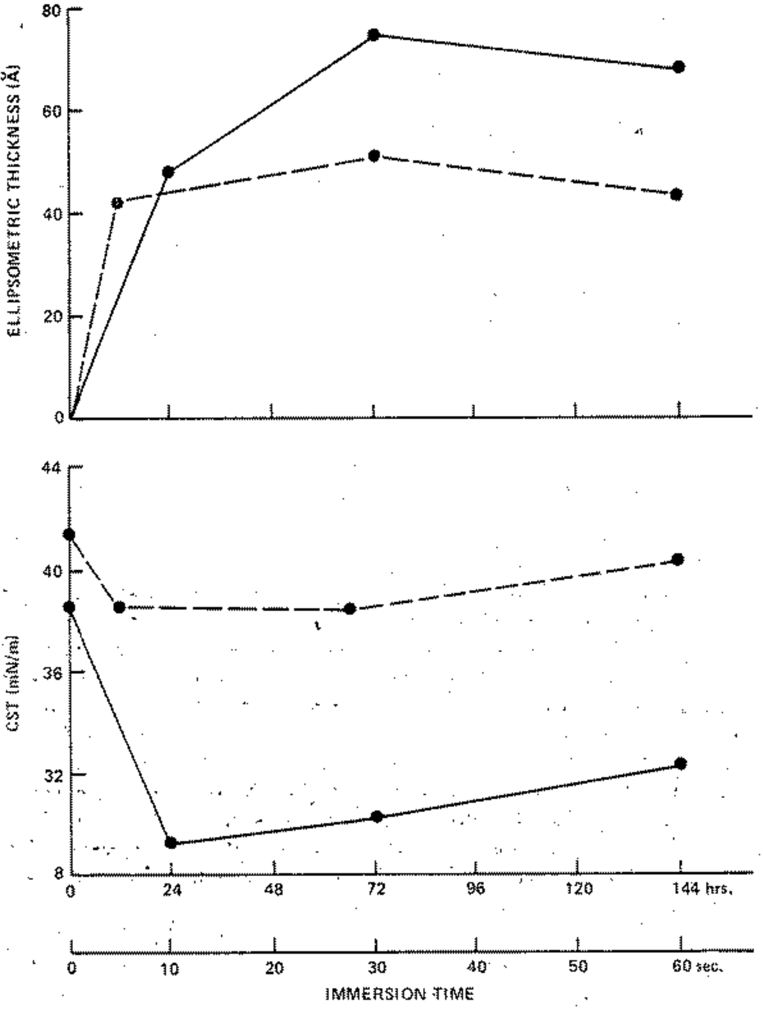


FIG. 8.—Comparison of ellipsometric thickness and critical surface tension data vs. time for the Gulf of Mexico (——●——) and fibrinogen (— — ● — —) adsorption studies.

via the Langmuir-Blodgett technique onto germanium. They represent films of one (PMG) and three (BaSt) layers in thickness. The obvious differences in the data lie in the CST, where the fatty ester film is much lower in CST. The contact potential data for PMG and barium stearate are relatively constant with film thickness (6) and, hence, the disparity in the film thicknesses appears to be unimportant to the purposes of our analysis. It is interesting to note that the contact potential for the seawater film and lipid are similar to each other and much lower than the values for the proteinaceous materials. The full interpretation of this electrical data (ΔV, contact potential) awaits further research into the molecular aspects of contact potential.

INFLUENCE OF SUBSTRATE SURFACE CHEMISTRY

It is logical at this point to consider the characteristics of films absorbed to surfaces other than germanium. In addition to its utility as a substrate for all of the surface chemical

TABLE 1

COMPILATION OF THE SURFACE CHEMICAL PARAMETERS FOR VARIOUS ADSORBED FILMS

Adsorbed film *Surface parameter*	*Gulf of Mexico (144 hr.)*	*Fibrinogen (60 sec.)*	*PMG* (α)	*Barium stearate*
CST (mN/m)	32.4	40.4	40.1	21.7
SLOPE (m/mN)	—0.020	—0.010	—0.015	—0.023
γ^d (mN/m)	30.3	41.4	38.8	23.8
γ^p (mN/m)	6.2	4.4	12.4	2.9
% γ^d	83.0	90.4	75.8	89.1
δ (Å)	68 ± 2	44 ± 3	20	75
ΔV (mV)	+ 164	+ 574	+ 380	+ 196

techniques outlined above, germanium that has been cleaned by detergent washing exhibits a surface energy that is approximately 50 % dispersive and 50 % polar in nature. The application of coatings onto germanium or the use of polymers in slab form affords the research scientist a full array of surface chemistry with which to experiment. We have followed this approach for nearly a decade and have discovered through empirical means that the degree of biological interaction with a surface varies with its surface energy according to the sketch drawn in Figure 9. This relationship, which reflects all aspects of biofouling, depicts a minimal adhesion of biomass to surfaces that are dominated by closely-packed methyl (—CH_3) groups or are highly hydroxylated. Such surfaces have critical surface tension values of between 20-30 mN/m. Surfaces outside of this range, namely the fluorocarbons ($<$ 20 mN/m) and the common commercial polymers (30 mN/m $<$ CST $<$ 45 mN/m) adsorb material in an «unfavorable» manner and never fully achieve passification of the biofouling process

The variability of biological interaction with substrate surface chemistry is readily seen in studies dealing with cellular adhesion. The tenacity with which the cells adhere to a substrate can be related to the surface properties of the substrates in the following way. In an unfavorable situation, the cells descend upon the surface and enhance adhesion by maximizing their *area* of contact. In the opposite case, the cells retain their relatively-spherical shape. Cell area is an important parameter that is generally confused with cell number. Oftentimes, under static conditions, the acceptability of an engineering material is judged by the *number* density of cells present on the surface. With «good» materials, most of these cells are removed when a shear stress is applied. Those cells that do remain are gen-

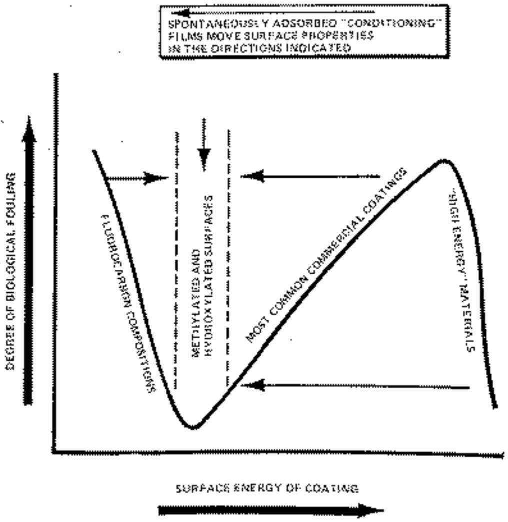
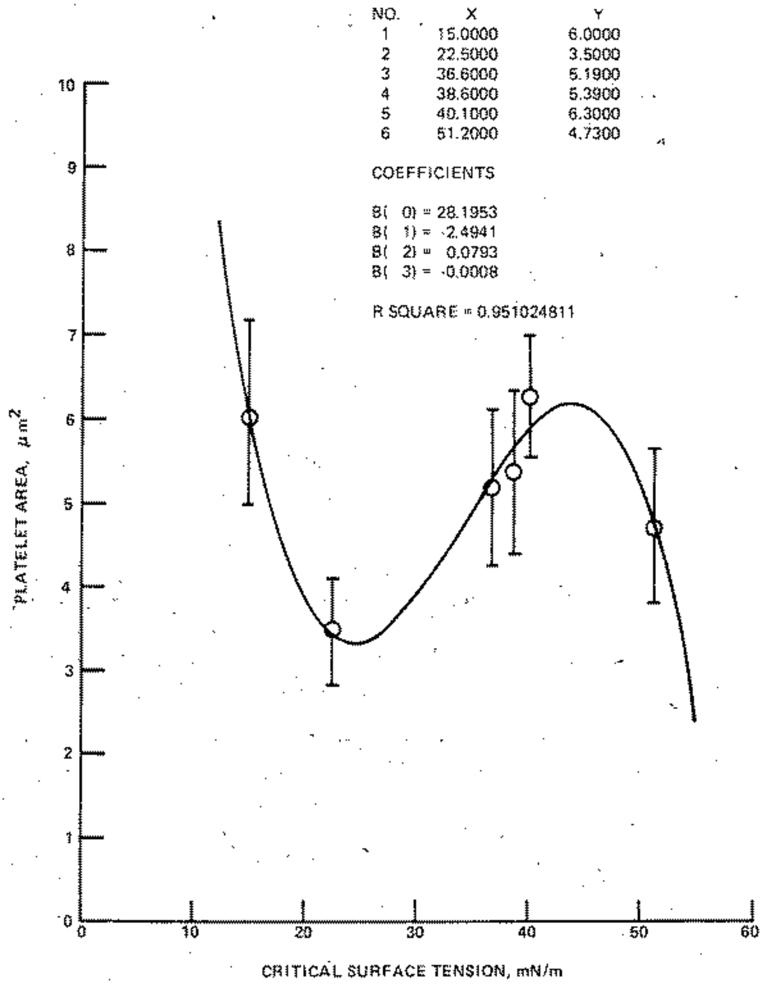


FIG. 9.—Influence of a coating's surface energy on fouling events (Reference 5).



NO.	X	Y
1	15.0000	6.0000
2	22.5000	3.5000
3	36.6000	5.1900
4	38.6000	5.3900
5	40.1000	6.3000
6	51.2000	4.7300

COEFFICIENTS

B(0) = 28.1953
B(1) = -2.4941
B(2) = 0.0793
B(3) = -0.0008

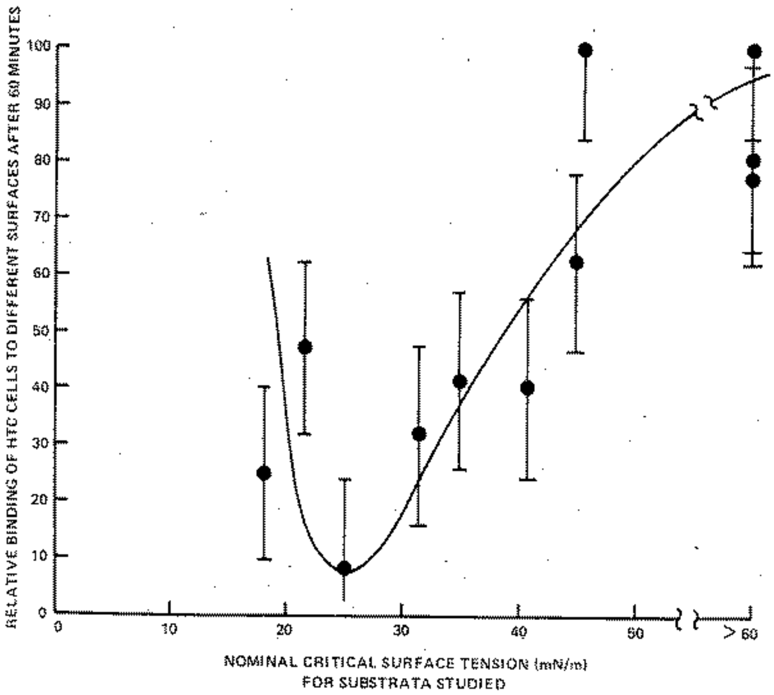
R SQUARE = 0.951024811

FIG. 10.—Plot of the measured platelet areas vs. the critical surface tension of the substrates (T = 37° C).

erally of a larger surface area. Hence, at this stage, cell surface area is the correct parameter to monitor in assessing the fouling resistance of the candidate surface.

In our study of the area of blood platelets adherent to surfaces of various surface energy, a relationship similar to Figure 9 emerged (see Figure 10). The reader will note that the minimal platelet area is found on substrates whose outermost chemistry reflects an energy value of approximately 25 mN/m. This number is characteristic of a highly methylated surface. In another study, GRINNELL *et al.* demonstrated the close correlation between cell surface area and cell adhesiveness as the substrate surface energy is modified (7) (see Figure 11). Again, the weakest cellular binding appears to occur on the methylated surface.

A further example of the influence of the substrate surface chemistry upon the acquired biofouling is illustrated by data shown in Figure 12. The shift of the measured surface energy of the test materials is shown in the Zisman plots in Figure 12. Note that the siliconized, low-energy substrate is already in the range for minimal bioadhesion prior to exposure to the seawater bacterial culture and hence, does not experience a dramatic shift in



RE-PLOTTED FROM DATA IN "STUDIES ON CELL ADHESION," F. GRINNELL, M. MILAM, AND P.A. SRERE, ARCH. BIOCHEM. BIOPHYS. 153: 193-198, 1972.

FIG. 11.—A typical correlation of the surface properties of various substrata with their relative support for biological adhesion (Reference 1).

surface energy indicative of the acquisition of a fouling film.

CONCLUSIONS AND RECOMMENDATIONS

The message that this paper hopes to relay is twofold: (1) the sequence of events leading to gross biological fouling follows a universal order, and (2) the surface chemistry of the substrate is influential in the manner and degree in which biofouling occurs.

All biofouling starts with the adsorption of a biopolymer from the biofluid. The manner of this surface modification appears to be related to the surface chemistry at the substrate and dictates the course of future events. On materials that are «acceptable» to the biofluid, a dynamic and reversible adsorption occurs which limits the extent of biofouling. Conversely, on «unacceptable» surfaces an irreversible polymer denaturation and fouling buildup occurs.

The manner of studying the interaction between an engineering material and a fouling solution appears to be best approached via the *in situ* technology of the surface chemist. By investigating the surface energy, contact potential, infrared absorption signature, thickness, x-ray diffraction characteristics and possibly electron microscopic appearance of an adsorbed film, the researcher can obtain some vital information as to the qualitative and quantitative aspects of this passivating layer.

Yet, clearly more detailed analysis needs to be performed. More biochemistry, biophysics, immunology and heat transfer technology needs to be infused into an *in situ* approach. With the application of thin layer immunoassay, biochemical staining coupled with densiometric analysis, and heat transfer approaches and continuing research into the meaning of contact potential, we hope to broaden our technical

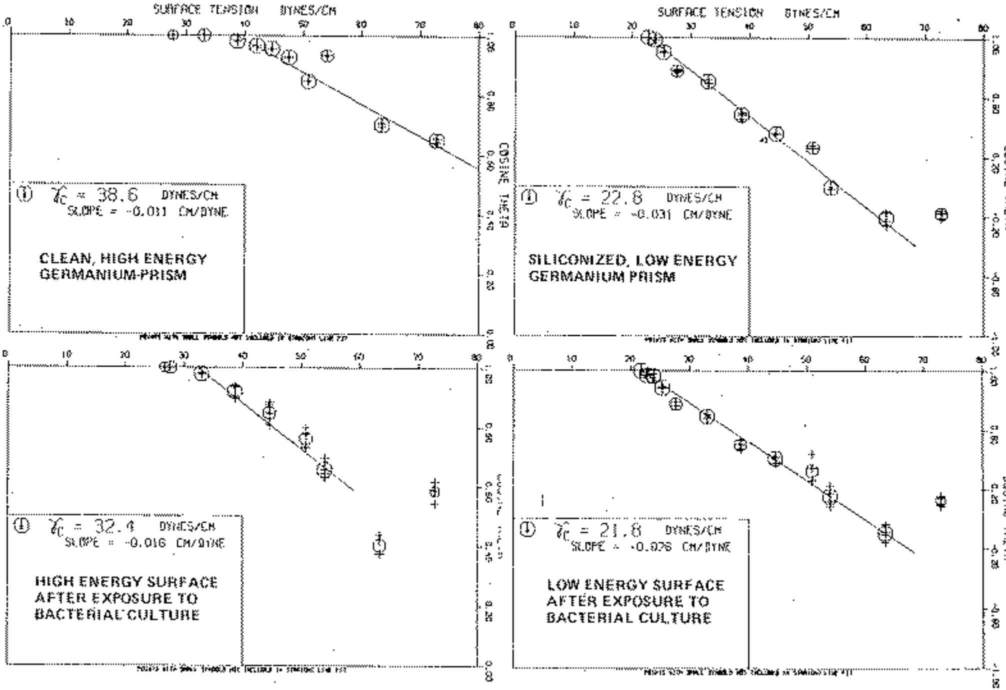


FIG. 12.—Wettability plots for high and low energy surface before and after exposure for 19 hours to seawater culture of pseudomonas SW1, marine bacteria. Adherent films were air-dried and distilled water rinsed prior to contact angle measurements.

approach and provide some additional answers to the bewildering questions of biofouling.

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