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Incidence of Fouling in Pearl Harbor

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INTRODUCTION

The fouling of the bottoms of ships, sea planes, and other marine craft and the obstruction of circulating water systems by sedentary organisms are not only annoying handicaps, but are matters of considerable economic importance. The problem is usually serious in tropical and subtropical latitudes, especially in quiet harbors where a narrow range of temperature encourages constant organic growth.

For many years casual observations on the fouling of ships in Pearl Harbor have been made by officials of the Navy Yard in the routine of dry docking and cleaning and repainting the hulls of various craft. Little critical study, however, has been made on the incidence of fouling in the harbor through systematic efforts over a considerable period of time. Almost no information relative to the biology of the organisms composing the fouling complex is available.

During the summers of 1935 and 1936 Dr. Paul Visscher carried on some experimental investigations of fouling in Pearl Harbor for the United States Navy. I have not had access to his report.

For a number of years, I have had the opportunity of observing fouling on ships serviced in the dry docks of the Navy Yard, and in 1935 began investigations in the harbor at the junction of the east and middle lochs.

In 1940 permission was granted me to begin a series of experiments at the coaling dock in the Navy Yard with a view to compare, in quality and quantity, the fouling there with that of the harbor area previously examined. Laboratory work was carried out at the Marine

Biological Laboratory of the University of Hawaii. Acknowledgment is due officials of the Navy Yard for providing material for the experiments and for many privileges which made possible the investigations. Thanks are also extended to W. H. Hammond, Senior Chemist of the Testing Laboratory of the Navy Yard, for helpful advice and cooperation.

To date, the scientific work bearing on this general problem, including the present report, consists chiefly of fact-finding surveys to determine the quality of fouling organisms at different stations in the harbor, the dominant forms, their rate of growth, seasonal succession, and early phases of development. No extensive remedial or preventative measures have been undertaken.

The observations herein reported were made at two localities in Pearl Harbor which will be designated as stations A and B. The water at station A is shoal, less than one fathom in depth at high tide, often turbid, and usually quiet or but slightly disturbed. The bottom is covered by silt and fragmented debris. This area is a suitable anchorage only for boats of very shallow draft. Test panels were suspended from the end of a privately owned pier extending about 50 yards from the shore. The panels were submerged near the bottom with no provision for studying fouling at different depths. As far as navigation is concerned, this station is the less important of the two and therefore will be treated with minor consideration.

Station B is about two miles nearer the entrance of the harbor than is station A. The water is approximately 15 feet deep at low tide, usually clear with good circulation. Test panels were suspended from the platform of the dock, and I was able to study fouling at different gradations of depth.

The predominant character of the fouling was noticeably different at the two stations during the periods of observation. Station A was characterized by a preponderance of barnacles with a considerable amount of algae, whereas at station B the prevailing fouling organisms, during most periods of the year, were serpulid worms. Numerous minor forms appeared in each area. Serpulid worms were usually present at station A but never attained the luxuriant growth typical of station B. Barnacles at station B did not reach the development in numbers or size of those at station A. The accumulation of algae was insignificant at station B.

At both stations were found bryozoans, including erect and encrusting forms; tunicates, both simple and compound; bivalve mollusks; hydroids; and sponges. Usually each of these groups was of minor importance but occasionally one or more would develop for a short time to the almost total exclusion of others.

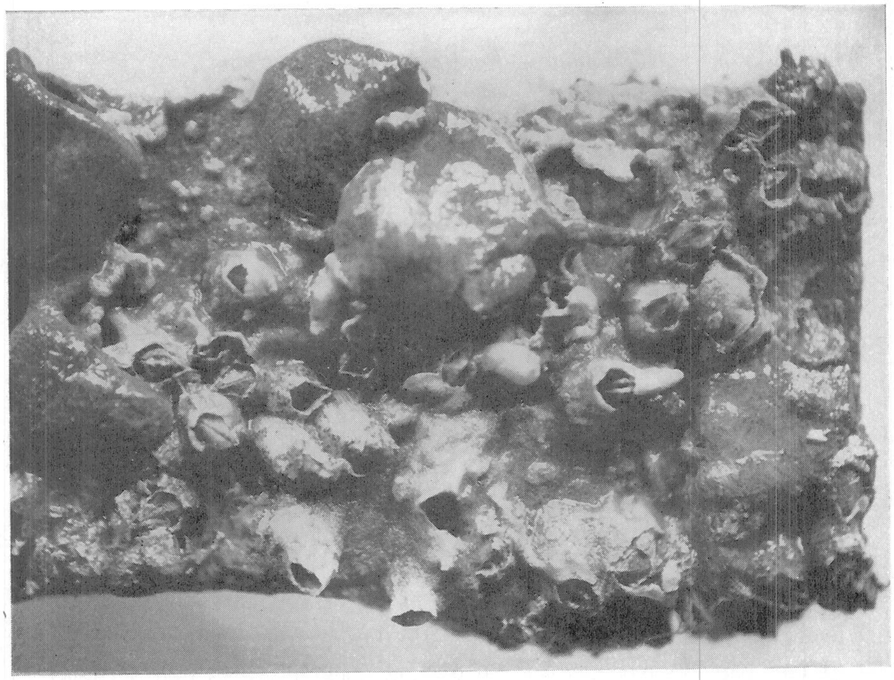
For the most part, test panels of wood of the standard size, 10 × 12 inches, were used to trap the fouling organisms. Plates of glass and sheets of various metals were also part of the equipment. Micro slides of glass, 1 × 3 inches, were convenient for catching and examining the early phases of sedentary organisms.

SERPULID WORMS

That serpulid worms with their secreted calcareous tubes constitute a serious fouling problem in a large part of Pearl Harbor, is obvious from a casual examination of material scraped from the bottoms of boats anchored even for a short time in these waters. An examination of test panels suspended at the coaling dock indicates that serpulid worms are the major fouling group of organisms in that area during most of the year, whereas only occasionally at station A were there heavy attacks of serpulid worms.

External coatings of worm tubes can be removed by the usual method of scraping after the ship has been placed in dry dock, but this involves a considerable loss of time. More trouble may ensue if the minute larvae of the worms enter submerged bearings of mechanical parts which have been inactive for a few days and begin the deposition of calcium tubes. Real trouble portends, however, when salt water circulating systems of ships become completely choked with masses of worm tubes, as they occasionally do.

Two species of serpulid worms settle on the bottoms of ships and on test panels in Pearl Harbor. The most common form seems to be *Hydroides norvegica* Gunnerus, a widely distributed species. Its tube, which may attain a length of 75 mm., is relatively thin, and mature tubes are usually characterized by two longitudinal ridges on the dorsal surface (fig. 1, *b*). The less common *Hydroides lunulifera* (Claparède) forms a thicker and longer tube which lacks the longitudinal ridges but which becomes roughened by circular costae in old age. In both species the animal occupies but a portion of the tube and when active extends its anterior extremity from the aperture, the pinnate



a

b

FIGURE 1.—Compound tunicates, barnacles, and serpulid worms: **a,** test panel submerged for 98 days, fouled by compound tunicates strongly competing with barnacles; **b,** panel fouled by the serpulid worm, *Hydroides norvegica,* during 35 days.

branchiae spreading like the petals of a flower. When disturbed, the worm withdraws into the tube and the aperture is closed by the operculum which is a modified branchia and functions as a stopper. The two species mentioned above are also distinguished by the character of their opercula (fig. 2, *a-c*).

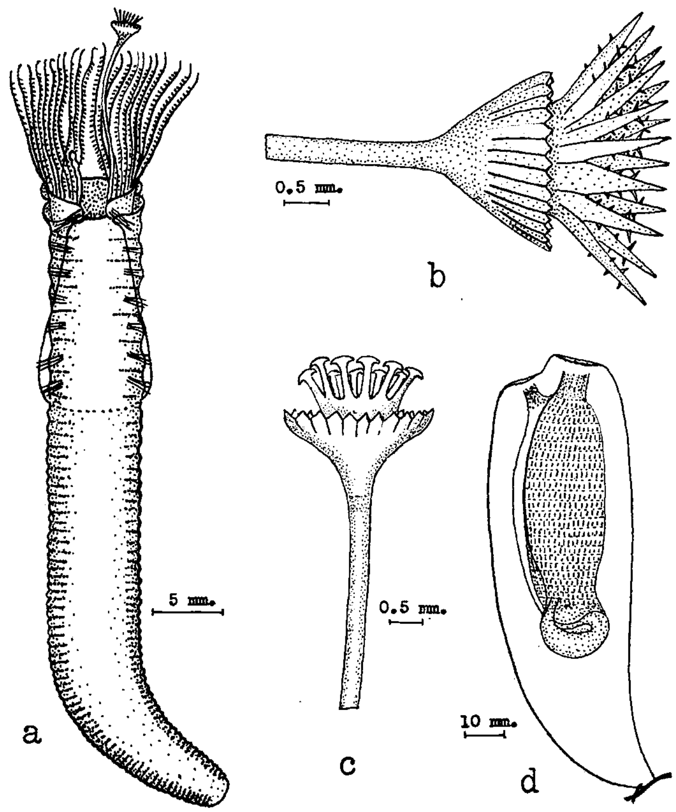


FIGURE 2.—Serpulid worms and tunicate: **a**, serpulid worm, *Hydroides norvegica*, removed from its tube; **b**, operculum of *H. norvegica;* **c**, operculum of *H. lunulifera;* **d**, a common tunicate with transparent tunic.

The mode of growth of serpulid worms is probably determined by crowded conditions as well as by tropic responses. In the early stages the tube is affixed to the surface throughout its length, but later it may rise at an angle to the surface and extend itself without support unless contact is made with adjoining tubes. When crowded, the tubes usually begin to rise from the surface after reaching a length of 25 to 30 mm., which may be attained in 20 to 30 days. In 60 days the tubes often stand out at right angles to the surface at a height of 50 mm. When the hull of a ship well covered by worm tubes in this state of development is moved through the water, an immense amount of friction is developed. Thus the animal benefits by greater aeration and the organism is protected from the possible accumulation of silt and from possible toxic elements of the surface.

On reaching a length of about 30 mm. the dioecious animals become sexually mature. Fertilization of serpulid worms was readily brought about under laboratory conditions by mixing mature ova and sperm. Almost at once the surface of the ova bristled with contacting sperm, the activity of which set up a rotary movement of the eggs. Within 30 minutes after union with the sperm the first cleavage stage divided the egg into two equal cells. One or two polar bodies usually were evident preceding the first division (fig. 3, *a-e*). Successive cleavage stages rapidly took place and blastulae were formed within four hours after fertilization (fig. 3, *f*). When observed 17 hours later, the trochophore stage had been reached (fig. 3, *g, h*). This phase probably followed the blastula within eight or 10 hours.

The typical trochophore of *H. norvegica* is quadrangular in outline from side view with an inflated equatorial zone, the slightly concave sides tapering toward each extremity. In end view the organism is circular in outline. A long flagellum projects from the anterior extremity and a whorl of strong cilia occupies the equatorial area. A prominent pigment spot is present anteriorly, and the outline of the digestive tract is visible. When first developed the trochophore swims high in the water, rotating rapidly on the long axis and exhibiting considerable flexibility in shape.

The trochophore stage persisted for at least eight days without much change except for a slight increase in size. Organisms of the same age varied somewhat in size, the larger ones being about 0.16 mm. in length when fully expanded (fig. 3, *h*). After four or five days of activity there is a tendency for the trochophores to swim lower in the water with some moving about in actual contact with the bottom. This behavior probably accompanies the initial transformation into the creeping form, which was observed 9 days after fertilization occurred. The trochophore becomes elongated to about twice its former length, the portion posterior to the equatorial area being extended and thickened. The flagellum and the ciliary zone become less conspicuous and the organism moves in contact with the surface by a creeping action (fig. 3, *i*).

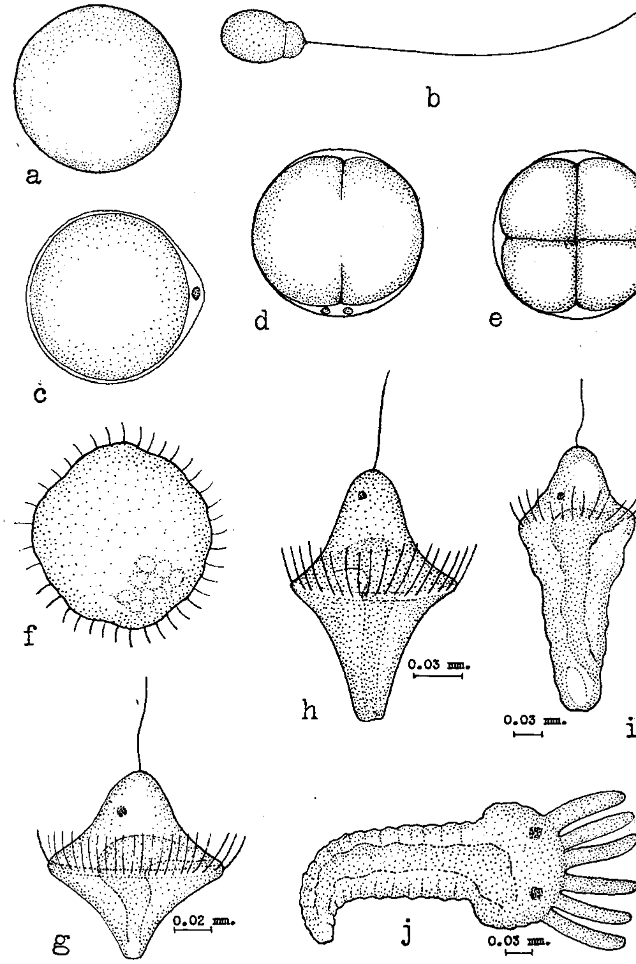


FIGURE 3.—Development of a serpulid worm: **a,** egg; **b,** spermatozoon; **c,** fertilized egg; **d,** first cleavage stage; **e,** four-cell stage; **f,** blastula; **g, h,** trochophores; **i,** transition of trochophore into worm, creeping phase; **j,** early phase of worm preceding tube formation. (*a-f,* greatly enlarged.)

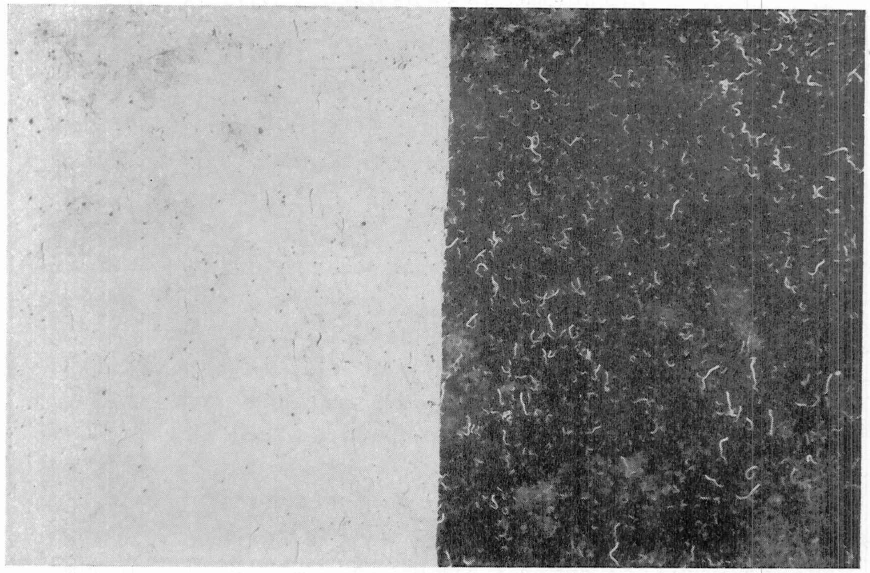
Twenty-four hours later transformation into a large-headed, creeping form with six prominent tentacles has taken place. Two prominent pigment spots mark the head region and there is evidence of segmentation (fig. 3, *j*). This is believed to be the phase just preceding the beginning of tube formation. The fixation of this form, the transition of tentacles into branchiae and operculum, and the initial secretion of a tube were not observed. Some evidence of the rapidity of these final changes, however, is shown by Edmondson and Ingram (3),[1] who obtained affixed serpulid worm tubes 3 mm. long on surfaces in over night catches of 12 hours duration.

There is a general belief, which is supported by considerable evidence, that fouling is greater on dark surfaces than on light-colored ones. The basis for this opinion rests on the supposed negative phototropism of the sedentary organisms at the time of attachment. For some of them, such as barnacles, this has been demonstrated by Visscher (9); but for other organisms—such as serpulid worms, bryozoans, tunicates, and mollusks—the responses of larval forms are not so clear or the experimental evidence so convincing.

A wood panel 10 $\times$ 12 inches, one side unpainted, one half of the other side coated with black and the other half with white non-toxic enamel, was suspended vertically just beneath the surface of the water for 9 days during October. On the painted side serpulid worms were quite evenly distributed over both black and white areas, but were somewhat more numerous on the black surface. On the black area the larger worm tubes were 12 mm. long, but the greater number were from 2 to 4 mm. in length. On the white area the longer tubes were 15 mm. in length but fewer smaller ones were attached here than on the black surface. That white or black makes little difference, however, in the response of the worms, is shown by the fact that many tubes cross the line from the dark to the light area or vice versa. On the unpainted surface the worm tubes are evenly distributed but less numerous than on either white or dark areas (fig. 4, *a*).

Another panel painted black and white (non-toxic) on one side was submerged for 30 days, October to November. The black surface was uniformly coated with worm tubes, the larger ones 35 to 40 mm. in length. They were piled upon each other in masses and some were beginning to rise from the surface. Among the larger tubes was a

[1] Numbers in parentheses refer to Literature Cited, page 34.



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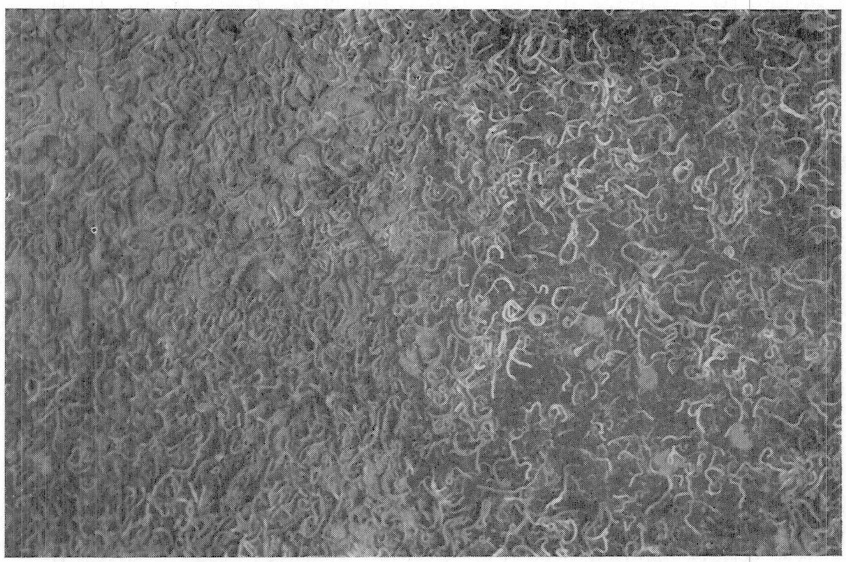


b

FIGURE 4.—Contrast of fouling on black and white surfaces; right half of each panel coated with non-toxic black enamel; left half coated with non-toxic white enamel: **a,** panel submerged for 9 days, black surface fouled slightly more than white; **b,** panel submerged for 30 days, white surface fouled more heavily than black.

dense setting of smaller ones from 5 to 10 mm. in length. The white area supported more worm tubes of the larger sizes than did the black surface, but fewer of the smaller ones. On the white surface many of the tubes 40 mm. in length were beginning to rise up at an angle (fig. 4, *b*).

Further development of serpulid worms was seen on a panel submerged at station B for 62 days, November to January. One fourth of the panel was coated with a plastic composition recommended by Johnson and McNeill (5) for inhibiting the penetration of shipworms. The formula consists of one part crude tar at 72° F., two parts cement, and four parts medium sand (dry). The remainder of the panel was unpainted. Both surfaces, including the area coated with the plastic composition, were completely fouled by serpulid worms which rose from the surface in masses to a height of 50 mm. (fig. 5, *a*).

That serpulid worms may settle upon and become attached to almost any kind of a surface is well known. They are readily collected on glass plates. Micro slides suspended in Pearl Harbor for 11 days during May became densely coated, the larger tubes being 20 mm. long (fig. 5, *b*). Affixed to similar slides during 21 days (November to December) worm tubes attained a length of 60 mm. (fig. 5, *c*). The greater accumulation of fouling organisms was always on the lower surface of the slides when they were suspended horizontally in the water.

During the investigations some panels were coated by antifouling commercial paints in order to compare fouling on such treated areas with that on untreated surfaces. The results were not always consistent. A panel with one half of one side coated with antifouling paint (Copper Red), the remainder untreated, was suspended vertically at station B for 16 days during October. In this period the unpainted surfaces accumulated a heavy coating of serpulid worm tubes which had begun piling upon each other in masses, the larger specimens being about 28 mm. in length. Only a narrow zone of the unpainted area next to the Copper Red border was free from fouling. The copper painted area was clear of fouling except for a slight encroachment of worm tubes on one edge (fig. 6, *a*).

After 42 days (October to December) a panel, one half of one side coated with Yacht Green antifouling paint and the remainder unpainted, showed heavy fouling on the painted surface. Serpulid

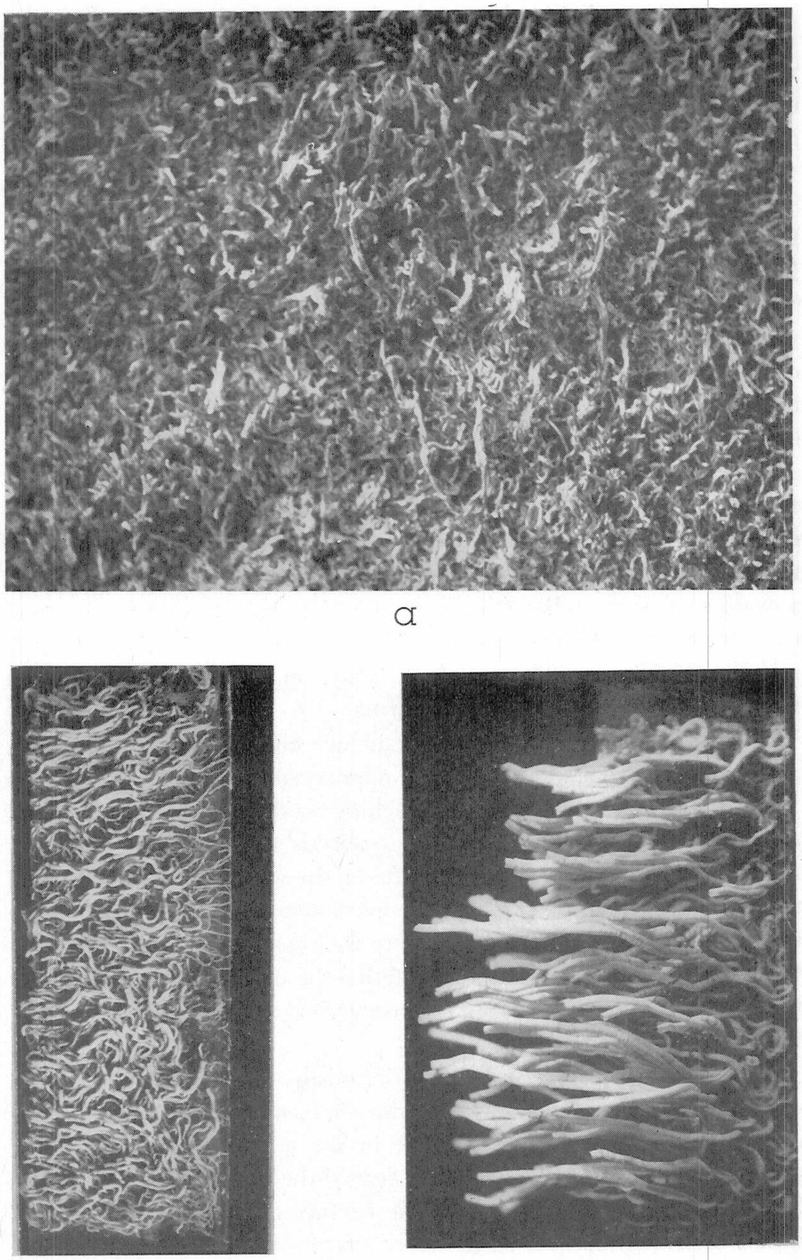


FIGURE 5.—Wood panel and glass plates fouled by serpulid worms: **a,** wood panel 10 × 12 inches submerged vertically for 62 days, left half coated by plastic composition, remainder untreated; **b,** glass micro slide, 3 × 1 inches, submerged horizontally for 11 days; **c,** similar slide submerged for 21 days.

worm tubes 30 to 35 mm. in length densely covered the surface, many of them beginning to rise at an angle. The fouling of the unpainted area was less than one half that covered by the antifouling paint (fig. 6, *b*).

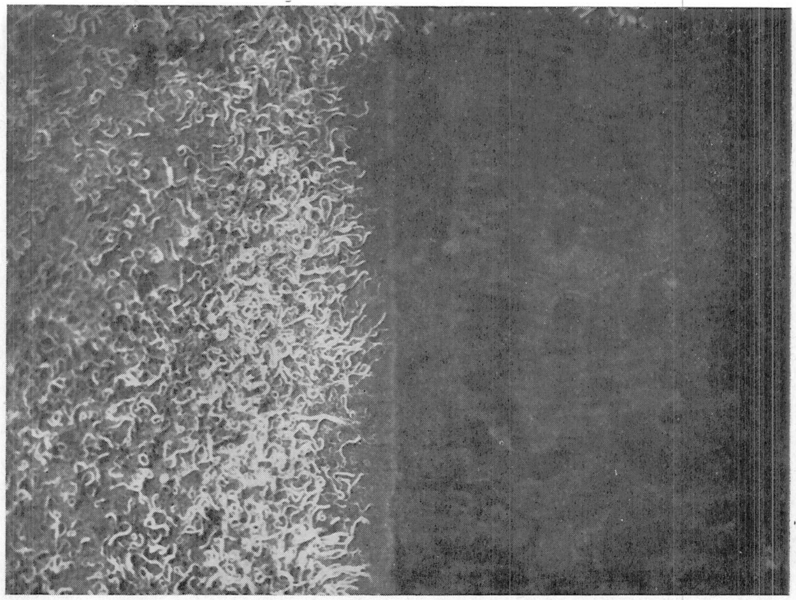
Another panel, one fourth of which was coated with Yacht Green, the remainder untreated, was submerged for 35 days, November to December. It was one of the most heavily fouled panels observed. Worm tubes densely covered the unpainted area, rising up at an angle with the surface to a height of 35 mm. The painted surface also was completely covered by worm tubes most of which, however, lay close to the surface. The antifouling covering apparently delayed the attachment of the worms for only a short period.

During a period of 49 days, March to April, Copper Red antifouling paint showed some slight influence in retarding the growth of serpulid worms. One half of each side of a panel was treated with this paint. On one side about one fourth of the painted area supported a coating of worm tubes (fig. 7, *a*). On the opposite side of the panel the Copper Red surface was densely covered by worm tubes rising to a height of 12 mm. The unpainted areas on both sides of the panel were heavily fouled by serpulid worms.

A panel with one half of one surface coated with Yacht Green and the remainder untreated was submerged for 32 days, April to May. It showed worm tubes encroaching on the painted area from all sides, probably indicating that the toxicity is reduced about the edges first. It is evident that when once affixed the worm can rapidly extend the tube over the toxic surface without danger to itself. Although the unpainted surfaces of this panel were well coated with worm tubes—the larger ones 30 to 40 mm. in length—the density of the fouling at this time was not so great as that occurring during the late fall and winter months (fig. 7, *b*).

Serpulid worms are sedentary organisms which usually show an optimum development at or near the surface of the water. Almost always there is a marked decrease in the quantity and the rate of growth of these forms within a few feet of the surface. Tests in which long panels were extended from the surface to near the bottom, and others in which separate panels were suspended at intervals from the surface to depths of 14 feet, usually gave similar results.

Four panels were submerged for 27 days (November to December) in a vertical series, the upper one just below the surface at low



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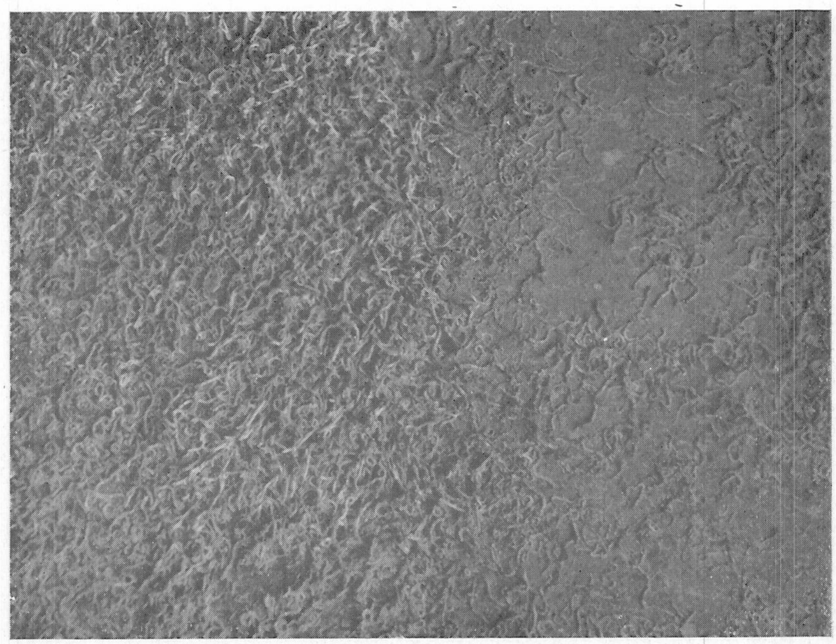
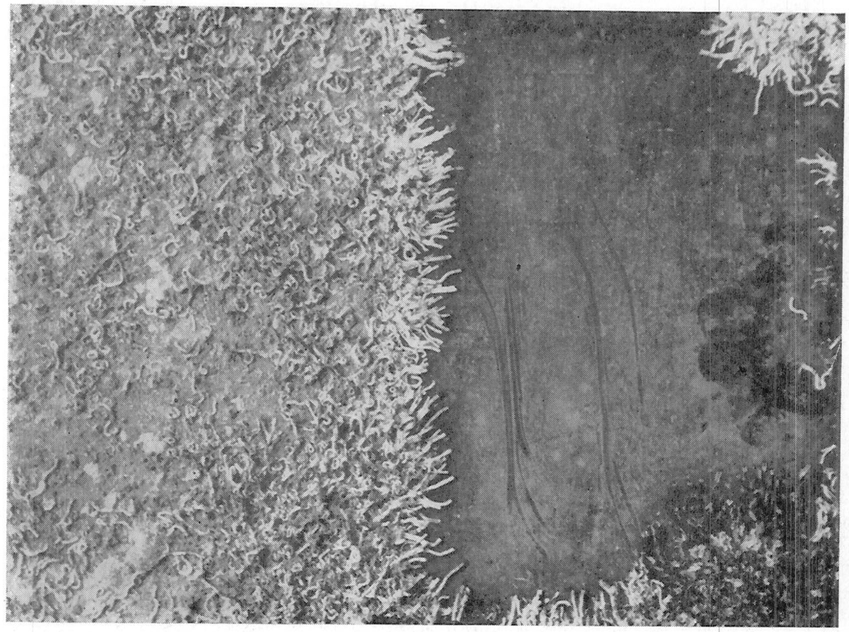


b

FIGURE 6.—Contrast of fouling on surfaces coated with antifouling paints with that on untreated controls: **a**, panel submerged for 16 days, right half coated with Copper Red, left half untreated; **b**, panel submerged for 42 days, left half treated with Yacht Green, right half unpainted.

FIGURE 8.—Contrast of fouling at the surface with that at a depth of 54 inches (station B): **a**, panel submerged vertically just beneath surface for 27 days; **b**, panel submerged as *a* but 54 inches below it.



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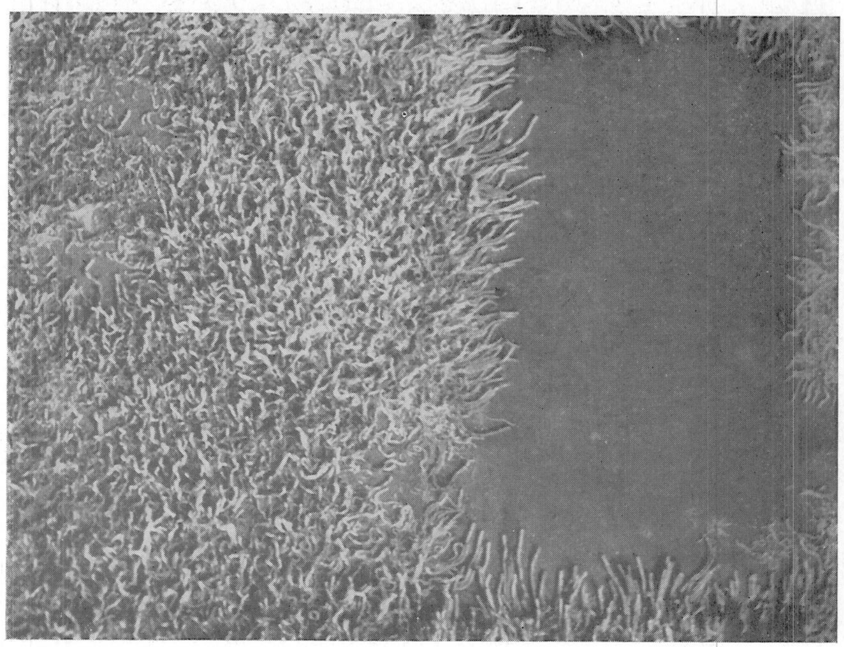

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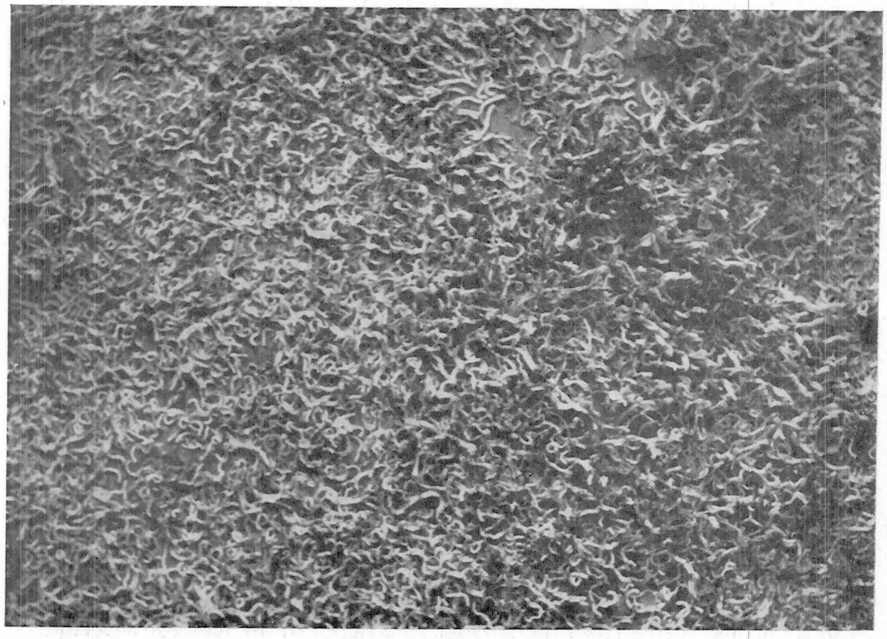
FIGURE 7.—Contrast of fouling on untreated areas with that on surfaces coated with antifouling paints; **a**, panel submerged for 49 days, right half coated with Copper Red; **b**, panel submerged for 32 days, right half painted with Yacht Green.



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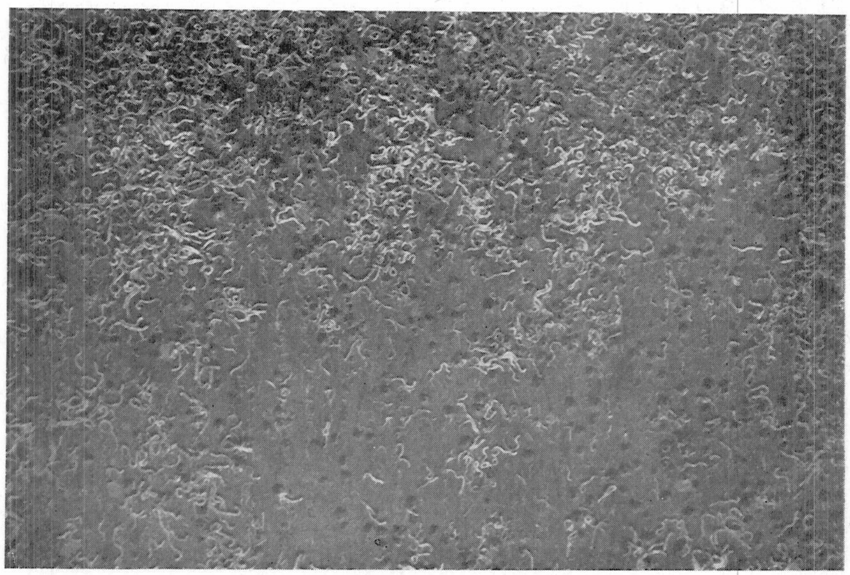


b

FIGURE 8.—Contrast of fouling at the surface with that at a depth of 54 inches (station B): **a**, panel submerged vertically just beneath surface for 27 days; **b**, panel submerged as *a* but 54 inches below it.

tide, the lower one 54 inches deeper. Fouling by serpulid worms showed a decreasing gradation in quantity from the surface downward, the upper panel having collected at least 5 times more fouling than the lower one (fig. 8, *a, b*).

An even greater contrast was seen on panels suspended at intervals from the surface to a depth of 9 feet, during 35 days, October to December. The upper panel was densely covered by serpulid worm tubes which extended outward 30 mm. from the surface, whereas on the deeper panel the worm tubes were few and scattered, the larger ones being about 25 mm. in length (fig. 9, *a, b*). Similar results were obtained in 13 days, November to December, on a panel extending from the surface to a depth of 12 feet. A marked difference in the quantity of serpulid worms at the surface and at a depth of 12 feet at station B was also seen in 51 days, March to May (fig. 9, *c, d*).

One experiment, however, presented some notable exceptions to the preceding observations. Fifteen panels were suspended at station B in a vertical series from the surface to a depth of 14 feet for a period of 21 days, November to December. Some panels were painted white, some black (non-toxic), others were coated with Yacht Green and Copper Red (antifouling paints), and others were unpainted. On each was a substantial setting of worm tubes, only slightly heavier on the upper six or eight panels. Especially on the painted areas, regardless of color or degree of toxicity, there was a large number of worm tubes from the surface down to and including the lowest panel. In this one observation, among many, the usual contrast between surface and depth, with respect to the development of serpulid worms, was entirely absent.

BARNACLES

In some localities about Oahu barnacles constitute the most important group of fouling organisms. This was usually found to be true in Kaneohe Bay (Edmondson and Ingram, 3). This is frequently the condition at station A in Pearl Harbor, but at station B the current observations have shown barnacles to be somewhat suppressed by other sedentary forms, especially serpulid worms. Because of their mode of growth and relatively slow development after attachment, barnacles are often overshadowed and rendered inconspicuous by rapidly developing serpulid worm tubes. On test panels near the sur-

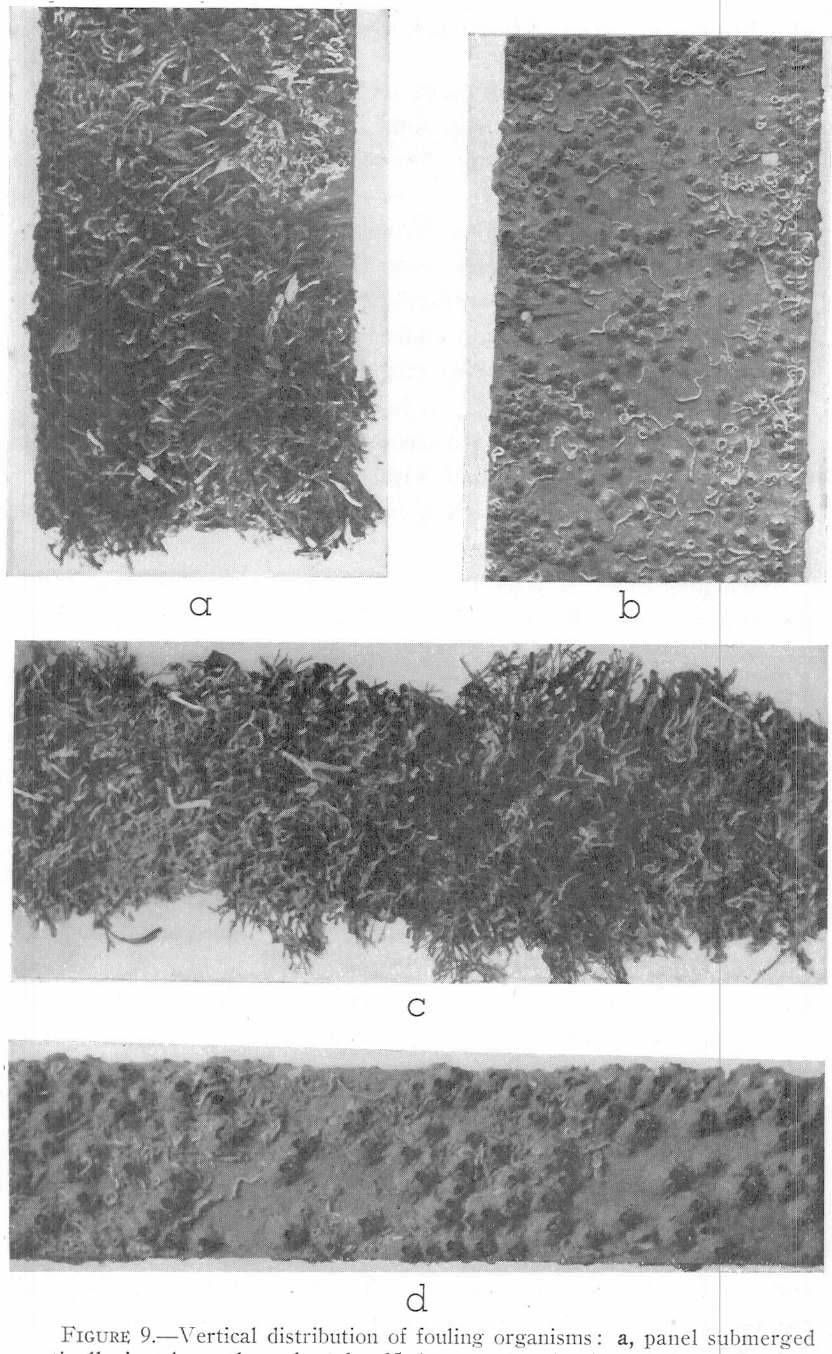


FIGURE 9.—Vertical distribution of fouling organisms: **a**, panel submerged vertically just beneath surface for 35 days; **b**, panel submerged as *a* but at a depth of 9 feet; **c**, panel submerged vertically just beneath the surface for 51 days; **d**, panel submerged as *c* but 12 feet below surface.

face of the water a dense setting of serpulid worms usually results in a paucity of barnacles, but the gradual fading out of worms at depths of from 4 to 6 feet permits an increasing development of barnacles at and beyond these levels.

At station B in Pearl Harbor barnacles were a significant factor in fouling only on panels submerged near the bottom. During periods of 9 to 16 days barnacles readily settled on near-surface panels and made a good start but were unable to attain normal maximum development in competition with fast growing serpulid worms.

Under optimum conditions, as in Kaneohe Bay or at station A, Pearl Harbor, the common barnacle (*Balanus amphitrite* Darwin) may reach a diameter of 24 mm. within the first year and increase in size but little after that although its life span probably is several years (fig. 10, *a-d*).

Spawning of *B. amphitrite* usually occurs for the first time when the shell reaches a diameter of 12 to 15 mm., which may be within one month after attachment under favorable conditions. The fertile monoecious organism releases large numbers of free-swimming nauplii, which show strong positive phototropic responses (fig. 11, *a, b*). After a period of time, probably a week or more, the nauplius is transformed into a cyprid which externally resembles somewhat a minute bivalve mollusk (fig. 11, *c*). This organism creeps about over the surface until it becomes attached at some suitable spot by its antennae. It is soon converted into the fixed barnacle stage. The investigations of Visscher (9) show that the cyprid, before becoming attached, exhibits negative phototropism which serves to explain why barnacles are more likely to become affixed on dark than on light colored areas.

Cyprids brought into the laboratory on panels in the evening are converted into young barnacles during the night. As the juvenile barnacle assumes form, the empty shell of the cyprid rests over its summit like a cap. This, however, is soon lost (fig. 11, *d*).

Test panels at station B, submerged for 9 days during October, presented an even distribution of barnacles over unpainted surfaces, averaging about 50 specimens per square inch of area. The larger specimens were 2 mm. in diameter. During this period, on non-toxic painted surfaces black areas supported slightly more barnacles than did white ones.

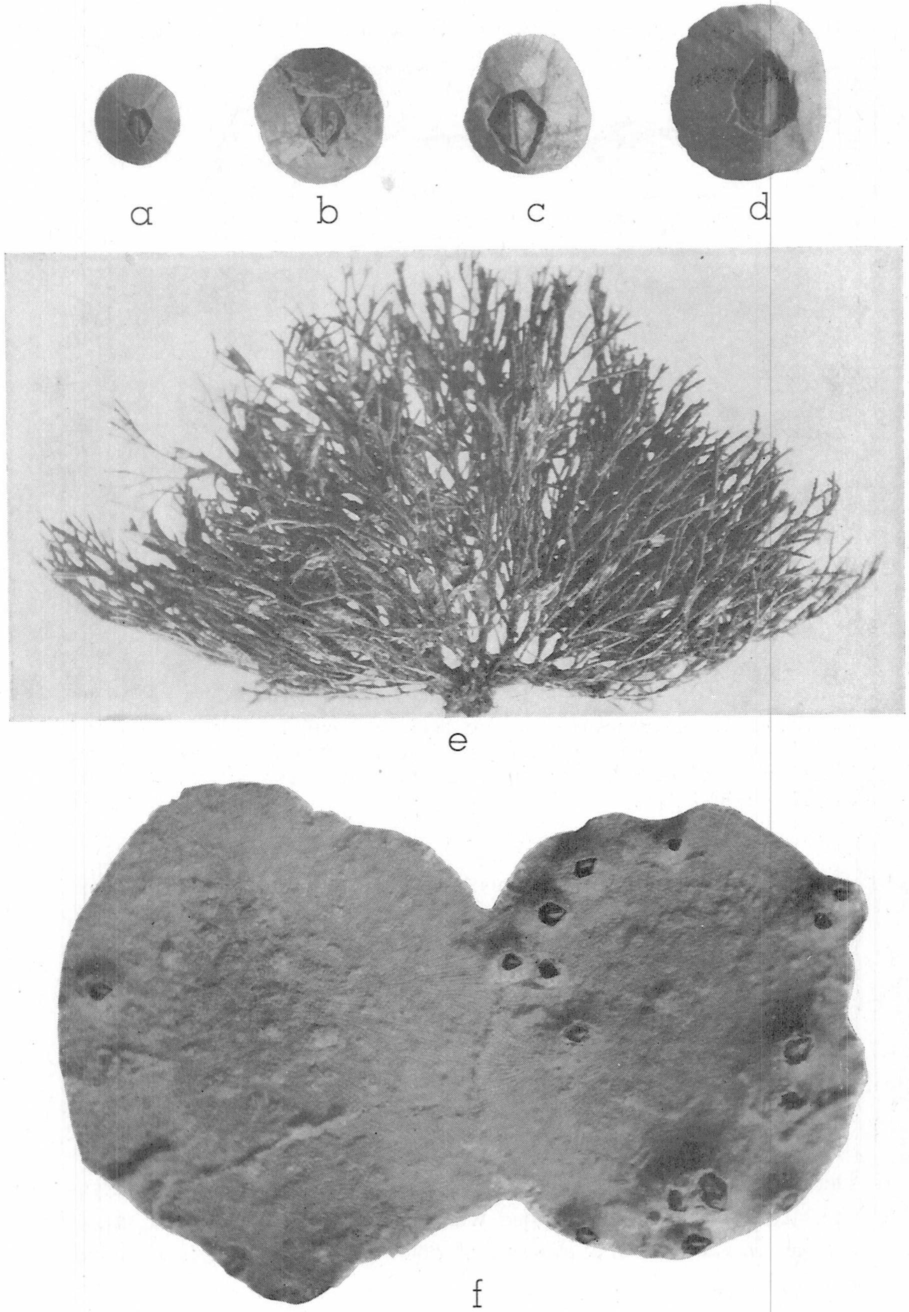


FIGURE 10.—Growth of barnacles and bryozoans: **a-d,** growth of barnacles during first, second, third, and twelfth month, respectively; **e,** growth of *Bugula* during 3 months; **f,** fused colonies of *Schizoporella* developed in 105 days. (All natural size.)

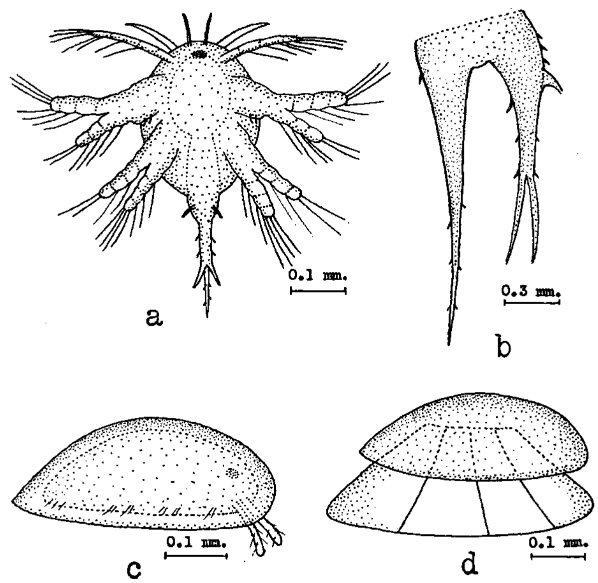


FIGURE 11.—Metamorphosis of barnacle: **a**, nauplius, ventral surface; **b**, lateral view of posterior extremity of nauplius, forked process ventral; **c**, lateral view of cyprid, preceding affixation; **d**, young attached barnacle capped by cyprid shell.

In 16 days many of the barnacles reached a diameter of 3 mm., and in 23 days some were 7 mm. in diameter. In 38 days a very few had attained a diameter of 10 mm. During these periods serpulid worm tubes were developing on the panels at a rapid rate. In a period of 30 days, October to November, on a panel densely coated with worm tubes, black and white surfaces accumulated about an equal number of barnacles, the larger ones 3 mm. in diameter. The worms were overriding the barnacles and probably deprived them of food and oxygen. At station B during one period of observation (141 days, December to April) under conditions very unfavorable to themselves, the largest barnacles developed were but 14 mm. in diameter, a size reached in Kaneohe Bay in less than one month, according to Edmondson and Ingram (3).

It is a common observation that on panels covered by non-toxic paints the external coloring of the shells of attached barnacles corresponds with the coating of the panel. This is because the cyprids burrow through the coating of the panel to become affixed to the solid surface, the plates of the shell of the barnacle lifting the colored paint as they expand.

From a limited use of commercial antifouling paints during the investigations, there is some evidence that such treatments have greater inhibiting effects upon barnacles than upon serpulid worms. Although there is no doubt that worms limit their development, there is still a suggestion that the absence of barnacles from some test panels is due to the antifouling coatings. Panels coated with Copper Red completely inhibited the attachment of barnacles as well as serpulid worms during 16 days in October. In 49 days, however, March to April, a few scattered barnacles became affixed to panels treated with Copper Red, the larger ones attaining a diameter of 3 mm. Other similar panels submerged for 51 days, March to May, were free from barnacles. During the periods of 49 and 51 days the painted surfaces were more or less heavily fouled by serpulid worms.

Treatments of panels with Yacht Green gave similar results, for the most part. During a period of 32 days, April to May, the affixation of barnacles was completely inhibited on surfaces coated by Yacht Green, although there was a good setting of worm tubes. In 35 days, November to December, panels treated in a similar manner were also free from barnacles. The settling of a few barnacles on a Yacht Green surface was noted during a period of 42 days, October to December, the larger specimens reaching a diameter of 3 mm. Here, during this time, the total fouling, chiefly worm tubes, was more than twice that of an untreated area of similar dimensions. At station A it was found that antifouling paints had considerable merit in the inhibition of the affixation of barnacles. According to Edmondson and Ingram (3) similar results were obtained in Kaneohe Bay, where serpulid worms were not a principal element in fouling.

On comparing panels submerged just beneath the surface at station B with those at a depth of about 14 feet, the greater development of barnacles is usually seen at depths of 6 feet or more below the surface. Serpulid worms normally find their optimum growth at more superficial levels.

It is readily observed that if barnacles maintain themselves under certain ecological conditions they must endure strong competition from

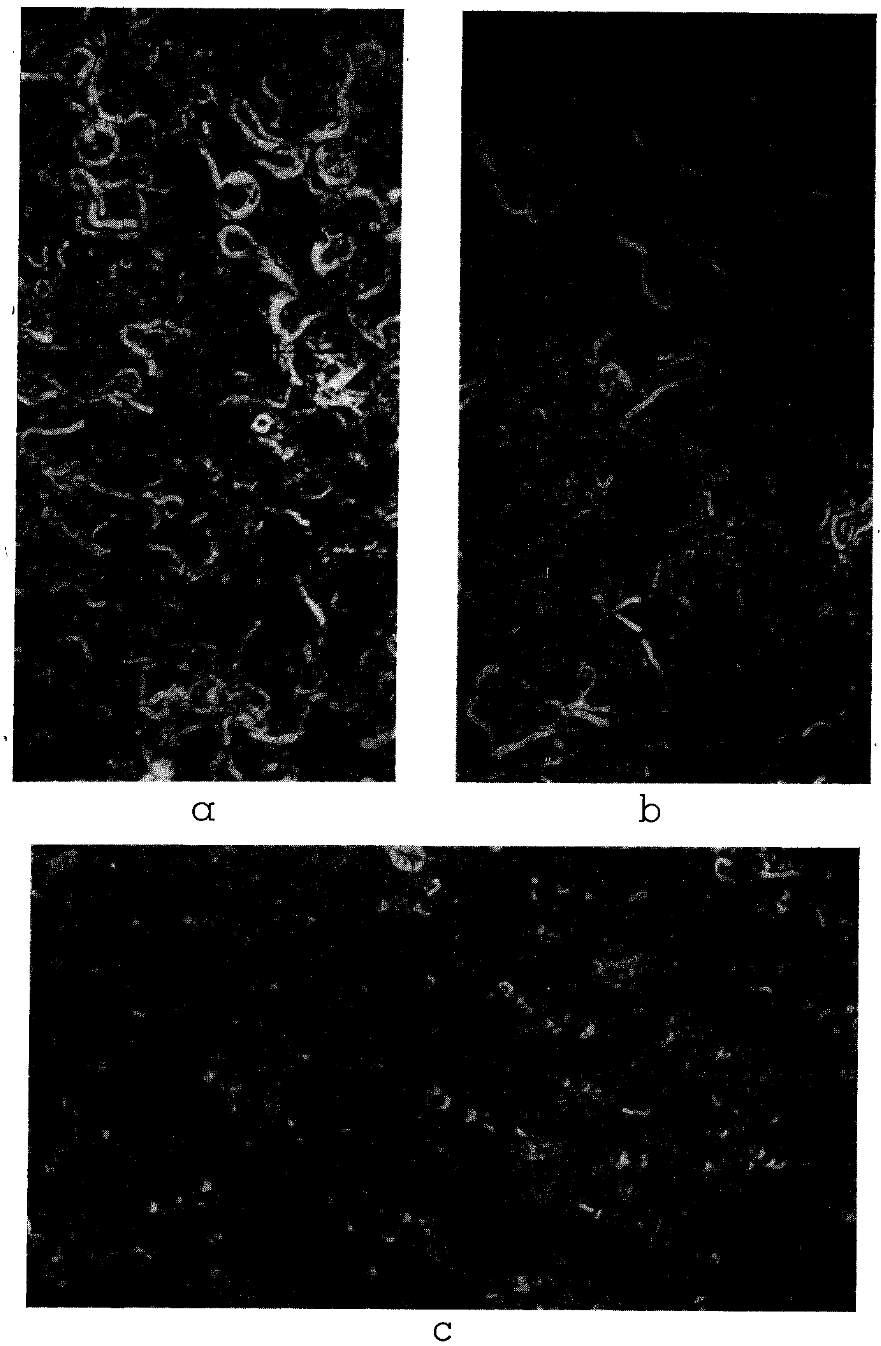


FIGURE 12.—Vertical distribution of fouling from surface to a depth of 12 feet during 13-day period: **a**, fouling on first submerged foot of panel; **b**, fouling at a depth of 8 feet; **c**, fouling at a depth of 12 feet.

other sedentary forms. Moore (6) points out that barnacles and sea weeds (*Fucus* spp.) are not suitable associates, as the sea weeds screen the barnacles and prevent their obtaining adequate food. In like manner, the rapidly growing worm tubes prevent the normal development of barnacles.

If the worms do not develop in sufficient quantity to smother the barnacles the latter may reach their maximum growth at or near the surface. This is shown on panels suspended from the surface to depths of 12 feet at station B for 13 days, November to December. Here, although worms became affixed in considerable numbers near the surface they were not crowded enough to hinder the development of barnacles which reached a diameter of 4 mm., about normal size, under favorable conditions (fig. 12, *a-c*). At the eight-foot level both worms and barnacles were fewer in number and smaller, the latter attaining a diameter of 3 mm. At a depth of 12 feet, few worms were affixed and the largest barnacles were but 2 mm. in diameter.

Another series of panels, extending from the surface to a depth of 54 inches, illustrates the competition between serpulid worms and barnacles. After being submerged for 27 days, November to December, the surface panel accumulated a heavy coating of worm tubes and scattered barnacles, the latter reaching a diameter of 3 mm. On the panel 54 inches below, a lighter development of worm tubes permitted an increased population of barnacles, the larger ones attaining a diameter of 5 mm. (fig. 8, *a, b*).

A clear inverse gradation between the development of serpulid worms and barnacles is seen in a series of 5 panels suspended at intervals from the surface to a depth of 9 feet at station B. The surface panel after 35 days, October to December, was heavily fouled by serpulid worms and *Bugula,* a bryozoan, and supported a few barnacles, the larger ones of which were 2 mm. in diameter. At a depth of 9 feet, with the worms almost faded out, the barnacles were thickly scattered over the surface, the larger ones being 12 mm. in diameter (fig. 9, *a, b*).

On a panel extending from the surface to a depth of 12 feet, during a period of 51 days, March to May, the first foot was heavily fouled by worm tubes and *Bugula* with a few barnacles, the largest of which were 3 mm. in diameter. The lowest foot of the panel, while almost free from worm tubes, was thickly set with barnacles, some of which were 14 mm. in diameter (fig. 9, *c, d*).

BRYOZOA (POLYZOA)

Among the common fouling organisms of Hawaiian waters are Bryozoa. A number of species are almost constantly present on the bottoms of boats or on experimental test panels. Some develop into upright branching structures, whereas others form flat, platelike colonies. One of the most familiar species is *Bugula neritina* (Linnaeus), a widely distributed form which develops into an erect, tufted colony several inches in height. If great numbers of these reddish-brown colonies cling to the bottom of a boat, its speed is much reduced. *Bugula* is abundant in Pearl Harbor, Honolulu Harbor, Kaneohe Bay and other coastal waters of Oahu (fig. 10, *e*). At station B the species often develops luxuriantly and may become a fouling organism second in importance only to the serpulid worm with which it is associated.

Colonies of *Bugula* are formed as a result of the affixation of minute, brown free-swimming larvae released from a mature organism. If attached at night, under laboratory conditions, by the following morning the larvae have been converted into moundlike or mushroomlike bodies 0.25 mm. in height. In 24 hours they develop into erect forms 0.75 mm. high with narrow stalks and present the beginning of a longitudinal suture which is to mark the separation of the first pair of zooecia (fig. 13, *a-e*). Twenty-four hours later the suture is complete with the young colony 1 mm. in height (fig. 13, *f*). A colony 1.25 mm. tall shows a rapidly growing tip which will become sutured to form a second zooecium (fig. 13, *g*).

The stem and branches of a colony of *Bugula* are composed of elongated zooecia which are fused with each other for the greater part of their length and arranged in a spiral fashion. Each zooecium encloses a complete monoecious animal (fig. 13, *j*). Colonies 4 mm. in height, composed of about 40 zooecia, may be developed in 9 days or less (fig. 13, *i*). When a height of about 25 mm. is attained the fertility of the colony is indicated by the appearance of spherical membranes or ooecia which are formed on the anterior edges of the zooecia (fig. 13, *h*). An ooecium is a protecting sheath enclosing the developing egg or embryo which is eventually released as a free-swimming larva.

Colonies of *Bugula neritina* frequently develop in large numbers on submerged surfaces in Pearl Harbor. They may reach a height of 100 mm. during a period of 3 months, which seems to be about the maximum age of the species in local waters. In laboratory cultures

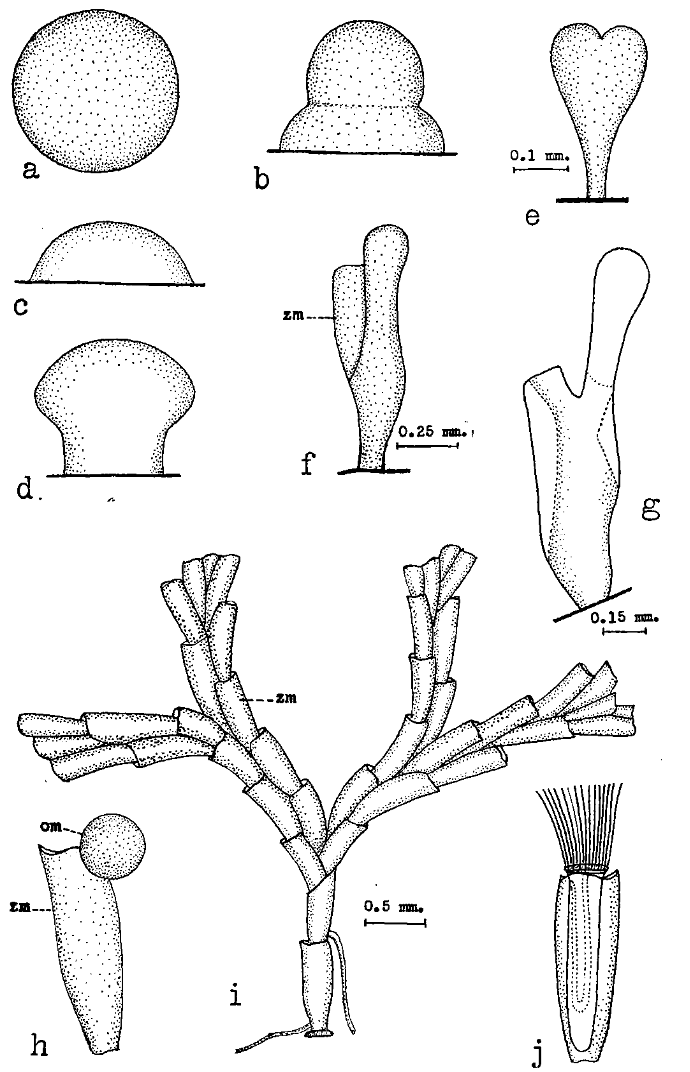


FIGURE 13.—Early stages of *Bugula neritina:* **a**, egg; **b-d**, phases shortly after affixation of larvae; **e**, four hours after affixation, showing initial suture; **f**, colony two days old, first zooecium formed; **g**, the same a few hours later; **h**, zooecium with an ooecium attached; **i**, colony 9 days old; **j**, zooecium enclosing an expanded animal. *om*, ooecium; *zm*, zooecium. (*a-d, h, j*, greatly enlarged.)

127 colonies have been counted on a surface 100 mm. × 24 mm. in area.

Bugula is nearly always associated with serpulid worms on experimental panels. There is very little competition between these two organisms as they both rise from the surface in the course of development, thereby gaining advantage over the close-clinging barnacle.

Antifouling coatings, such as Copper Red and Yacht Green, at times show little efficiency in repelling the attachment of larvae of *Bugula*. In other experiments the paints have delayed the affixation of the organisms, but the properties repugnant to the larvae apparently do not last long. Some of the largest colonies of *Bugula* I have observed were attached to supposedly toxic surfaces.

Observations on the vertical distribution of *Bugula neritina* at station B show that the species reaches its maximum development near the surface of the water. During a period of 35 days, October to December, surface panels supported many colonies of *Bugula* 40 mm. in height, whereas none was found at a depth of 9 feet (fig. 9, *a*, *b*). On other panels, during 51 days (March to May), the first foot below the surface was heavily fouled by serpulid worms and *Bugula*, colonies of the latter being 35 mm. in height. At a depth of 12 feet few worms and no colonies of *Bugula* were attached (fig. 9, *c*, *d*).

Encrusting forms of Bryozoa forming flat, circular colonies are also common sedentary organisms likely to become fixed to the bottoms of boats and to experimental panels. In Hawaiian waters the prevailing species, probably *Schizoporella unicornis* (Johnston), often forms colonies 2 or 3 inches in diameter, spreading rapidly over smooth areas or over the shells of barnacles, tubes of serpulid worms or other irregularities of the surface (fig. 10, *f*). Since the colonies cling closely to a surface, the friction caused by them is less than that produced by erect colonies of *Bugula* or by masses of worm tubes.

The early stages of encrusting forms of Bryozoa may be obtained by submerging panels in the water for a few hours only, either day or night. After the affixation of a free-swimming larva the initial zooecium is quickly formed, serving as a basis for the colony. From this basic zooecium a thin transparent foundation is secreted, giving rise to a second chamber, and successive ones are formed in a similar manner (fig. 14, *a-i*).

Observations on the rate of growth of the common species have been made, and the following information may be considered normal under favorable conditions. On panels submerged for 6 days colonies

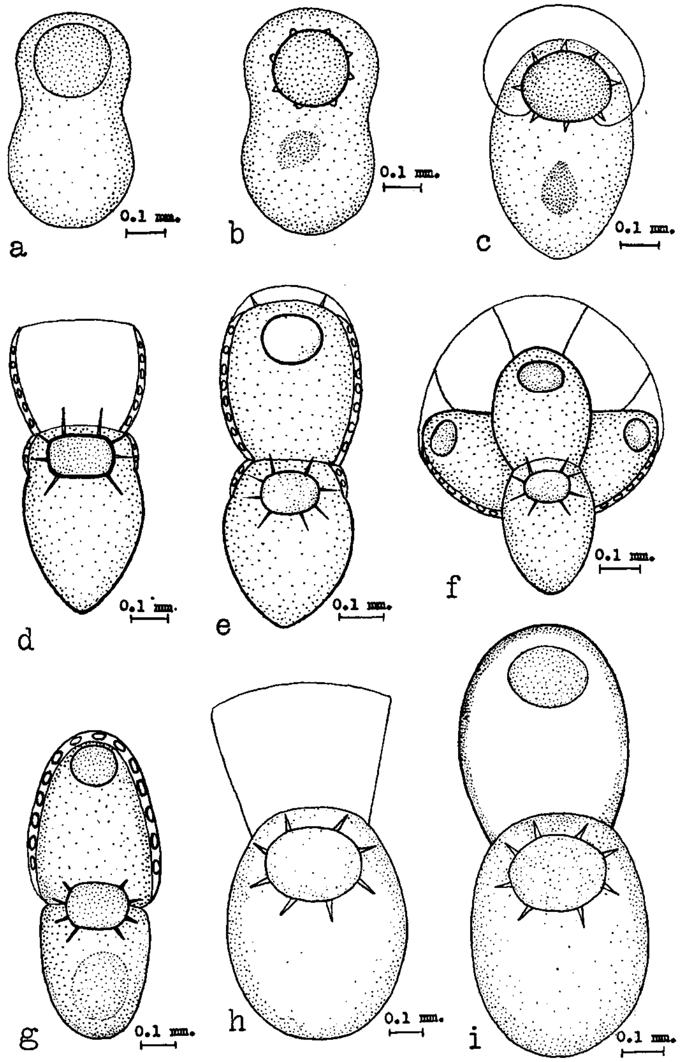


FIGURE 14.—Early phases of encrusting Bryozoa: **a-c**, affixed phase of initial zooecium at intervals of a few hours; **d-f**, three successive phases of a young colony within a period of 14 hours; **g**, a young colony shortly after affixation; **h-i**, phases of another colony at an interval of 24 hours.

2 mm. in diameter are developed; in 69 days a diameter of 50 mm. may be attained; and in 3 months many colonies exceed 60 mm. in diameter. If large numbers of larvae become affixed on a surface at about the same time, the resulting colonies may fuse and form an almost solid encrusting layer. During 26 days, August to September, no less than 200 colonies were established on one surface of a wood panel 5×7 inches in area.

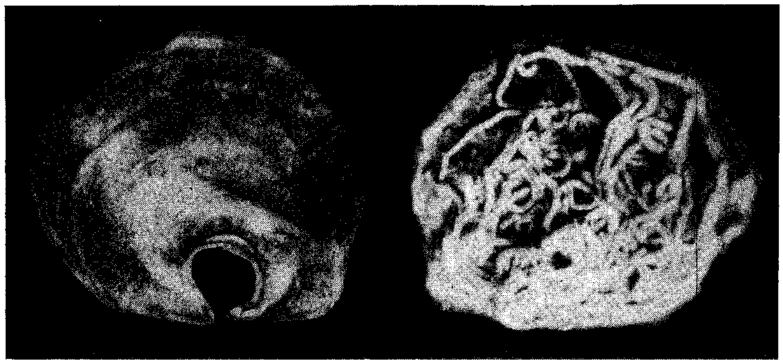
In tests of vertical distribution colonies of *Schizoporella* developed best near the surface, if competition with other organisms was not too severe. In short periods, up to 13 days, on panels extending from the surface to a depth of 12 feet, colonies of encrusting Bryozoa were more abundant and much larger in the upper levels than at greater depths. There was not yet sufficient time for dominance by serpulid worms. However, another experiment (51 days) showed that numerous colonies of *Schizoporella* were established at a depth of 11 feet, where worm tubes were few, whereas none was observed at the surface where serpulid worms densely fouled the panel.

MOLLUSCA

Two species of bivalve mollusks, *Anomia nobilis* Reeve, and *Ostrea sandvichensis* Sowerby, are potentially important fouling organisms in Pearl Harbor. They constitute a substantial part of the material scraped from the bottoms of some boats after they have been anchored in the harbor for some time.

Of the two mollusks, *Anomia* is seen on the hulls of boats more frequently than is *Ostrea*, and this fact may be accounted for by its mode of life and rapid development. *Anomia* is recognized by the flat, circular shell, the lower valve of which is perforated by a hole through which the byssus passes in attaching the mollusk to its support (fig. 15, *a, b*). There is a tendency for individuals, when the fouling is heavy, to pile upon each other forming clusters several inches deep which would greatly increase the friction of a boat moving through the water.

Opportunity for the study of the larval phases of *Anomia* was not provided during these experiments, hence only the rate of growth after affixation was observed. At station B, the species was constantly present on test panels and under favorable conditions grew rapidly (fig. 15, *c*). In 10 days, specimens of *Anomia* reach 2 mm. in long diameter of shell. In 23 days a diameter of 8 mm. may be attained, 15 mm. in 32 days. Panels submerged 42 days have supported shells 24



a b

c

FIGURE 15.—*Anomia nobilis:* **a, b,** lower and upper valves, respectively. natural size attained in about 3 months; **c,** panel lightly fouled by *Anomia* in 72 days at station B.

mm. in long diameter, and within 141 days the species has deposited shells 48 mm. in diameter, which probably is near the maximum size. Dall, Bartsch, and Rehder (2) list a Honolulu Harbor specimen 57 mm. in long diameter of shell.

The native Hawaiian oyster, *Ostrea sandvichensis,* is abundant in certain parts of Pearl Harbor and may become attached to boats which have been stationary in the harbor for considerable periods of time. I saw a decommissioned naval vessel which had been anchored for 5 years in Pearl Harbor, the hull of which was almost solidly coated with masses of this oyster several inches in thickness. Apparently, however, the mollusk is not a fouling menace in the vicinity of station B, as at no time during the observations has it been affixed to test panels.

TUNICATES (ASCIDIANS)

Tunicates, both simple (single) and compound (colonial), are frequently associated with other sedentary organisms in the fouling complex. During periods of rapid development in local waters, simple tunicates may necessitate the cleaning of the hulls of ships at intervals of three or four months.

Several forms of simple tunicates, undetermined as to species, appear on test panels at intervals during the year at station B. An erect species with transparent tunic is frequently seen (fig. 2, *d*). It has attained a length of 30 mm. in 21 days and 50 mm. in 60 days. Some specimens 5 inches long probably developed within a period of 6 months. Boats anchored in Pearl Harbor for a few months sometimes have their hulls densely fouled by this tunicate to the almost total exclusion of other organisms.

There are also many compound tunicates of undetermined species in local waters. Some are brilliantly colored spreading over a surface in a soft gelatinous layer, whereas others form globular masses several inches in diameter (fig. 1, *a*). Imbedded in the investing mass are the individual members of the colony which may or may not be grouped in systems. An increase in size takes place by budding, the individuals of the colony not developing separate tunics but being held together by the fleshy mass. Bulbous colonies have attained a diameter of 70 mm. in 60 days in local waters.

The tunicate represents a chordate organization which reaches its highest development in the tadpole or larval phase during which period the organism possesses a notochord in the tail (fig. 16, *d-e*). Fixed

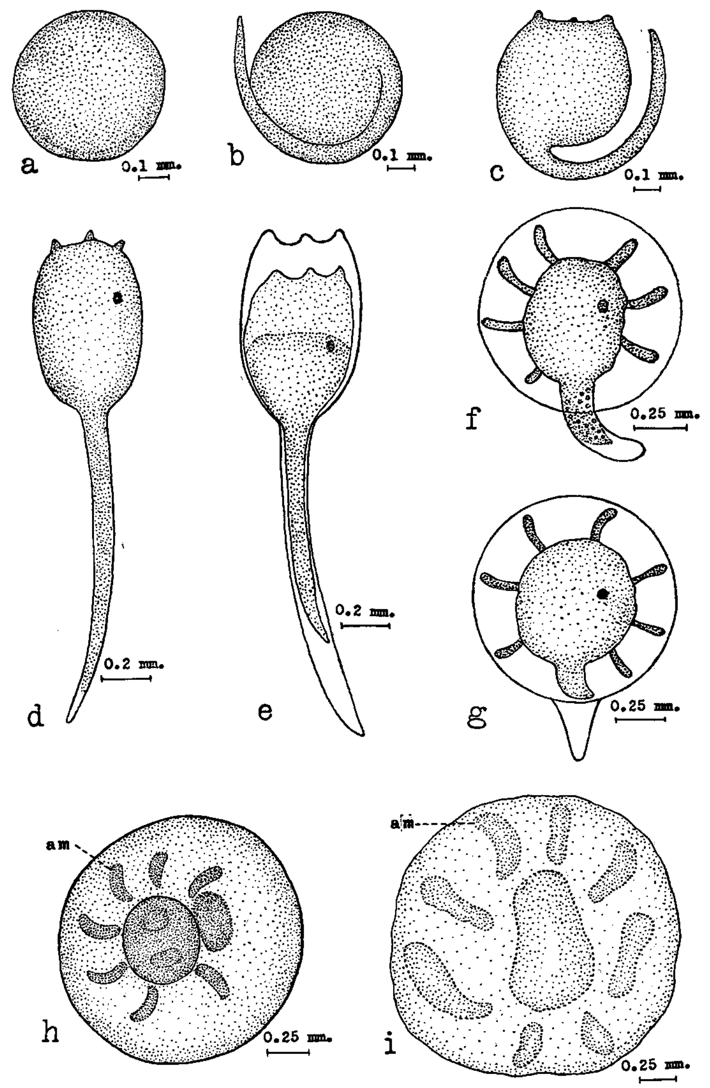


FIGURE 16.—Early development of compound tunicates: **a**, egg; **b**, **c**, tadpole stage evolving from egg; **d**, active tadpole stage; **e**, tadpole shortly before affixation; **f**, **g**, development following settling of larvae, about 14 and 20 hours, respectively, after affixation; **h**, **i**, later phases of two colonies. *am*, ampulla.

adult individuals or colonies result from the attachment and metamorphosis of the free-swimming larvae. With the affixation of the larva the organism degenerates into a non-chordate form, the tail and notochord becoming atrophied.

In the metamorphosis of a compound form, as observed, the unfolding of the tailed larva occurred after the egg had left the body of the parent (fig. 16, *a-c*). The duration of the free swimming period of the larva is uncertain but after affixation the transformation following is rapid. Larvae becoming attached at night are small colonies on the following day, ectodermal ampullae have made their appearance and the organism expands into a gelatinous mass. The future colony is developed by budding from the initial member (fig. 16, *f-i*).[2]

AFFIXATION OF ORGANISMS

Various factors, chemical and physical, have been suggested as being influential in the affixation and metamorphosis of sedentary organisms. Visscher (9) demonstrated that the cyprid stage of the barnacle is negatively phototropic which supposedly accounts for the excessive accumulation of the organisms on dark rather than light surfaces. My experiments in Hawaiian waters have generally substantiated this fact. Pomerat and Reiner (7) have recently emphasized the photic factor by comparing day and night catches on black, opal, and clear glass plates. With daylight contacts, twice as many barnacles were affixed to the black surface as to either of the others, but little difference in number was observed as a result of night exposures.

With respect to the oyster, Prytherch (8) pointed out that small amounts of copper constituted a definite stimulus for affixation and metamorphosis, which suggests that trace elements of one kind or another may possibly function in a similar manner in the attachment of other sedentary forms. Hopkins (4) ascribed the greater accumulation of oyster spat on the lower than on the upper face of a horizontal surface to the swimming position of the larva with the foot directed upward. Hopkins saw no phototropic response in the behavior of the oyster larvae.

The view that the formation of a film of slime produced by bacteria, algae, and other organic matter must precede the affixation of sedentary organisms has had considerable support. The work of Angst (1) suggested a direct relationship between the bacterial film and the

[2] See Phil. Trans. Roy. Soc., B, series "Studies in tunicate development", pts. I-V, by N. J. Berrill, 1929, 1931, 1935, 1936.

appearance of attached forms. His conclusion was that barnacles did not become affixed to a surface in advance of the slime as its presence was necessary for the development of the young organisms.

After extensive experiments ZoBell (10, 11) concluded that a primary film encourages the attachment of sedentary forms. Advantages of the bacterial film, as indicated by ZoBell, include: supplying a foothold for larval organisms and food for their development; discoloring bright surfaces thereby encouraging the attachment of negatively phototropic forms; protecting fouling organisms from toxic elements of the surface; increasing the alkalinity of the surface which may stimulate the deposition of calcareous material; influencing the potential of the surface thereby attracting larval forms, and favoring the growth of algae by the concentration of plant nutrients.

That the formation of the film begins almost at once after a surface has made contact with the water, is indicated by the short time required for the initial attachment of fouling organisms. Only a few hours, day or night exposures, are needed for submerged test panels to collect a considerable number of sedentary forms. An interesting phenomenon associated with a surface coated by non-toxic enamels is mentioned on pages 20-21. Frequently on panels so treated barnacle cyprids, instead of becoming attached to the surface where the bacterial film has supposedly formed, burrow through the slime and the underlying coating of enamel as well, to settle directly upon the solid surface of the panel. Here, apparently, has been set up an initial stimulus of activity rather than a stimulus of attachment. It appears that the cyprids are seeking a foothold other than that offered by the bacterial film. Whatever may be the role of the primary film in activities of this nature, obviously it may provide food for the growing organisms.

SUMMARY

Preliminary studies in Pearl Harbor indicate that barnacles are most prominent in the fouling complex at the junction of the east and middle lochs (station A), whereas serpulid worms prevail in the vicinity of the coaling dock (station B).

The rate of growth of various sedentary organisms in Pearl Harbor is noted and some phases in the metamorphosis of certain forms are recorded. Measures designed to inhibit affixation of the organisms must take into consideration the responses of the larvae.

In the fouling association one organism may be a limiting factor in the development of another. In competition with serpulid worms and

compound tunicates, forms like barnacles—which cling close to the surface—usually succumb, because they are smothered by the others.

Serpulid worms reach their maximum development immediately beneath the surface of the water. Barnacles, under these limiting conditions, may develop more fully at depths below normal for the worms.

Bryozoa, both erect and encrusting forms; the molluscan species, *Anomia nobilis;* and tunicates, both simple and compound, usually are associates of serpulid worms and barnacles in Pearl Harbor. Only occasionally do they play more than a minor role in the fouling complex.

Limited tests with commercial antifouling paints indicate that they are effective in preventing fouling for short periods of time only. There is evidence that these coatings, as used, repel barnacles more efficiently than they repel serpulid worms.

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