CHAPTER 1

The Effects of Fouling

Fouling results from the growth of animals and plants on the surface of submerged objects. Its most widely known effect is on the efficiency of propulsion of ships, but there are many other ways in which it produces difficulties. Thus the fouling of the underbody of flying boats may result in their inability to get off the water. Growths may interfere with the mechanisms which actuate mines and reduce the efficiency of underwater acoustic devices. The drag of currents on fouled cables may cause mines to "dip" below their intended depth, and similar difficulties are encountered in maintaining defensive nets. Fouling gives serious trouble when it occurs in pipes and conduits used to conduct water both in ships and in industrial installations on shore. The growth may have undesirable effects as the result of destruction of the protective coatings intended to reduce corrosion, and may indeed increase the corrosion of unprotected metal itself.

In a limited number of cases, the tendency for submerged objects to foul may be put to advantage as is the case in the shellfish industry. In mine warfare the fouling may act as camouflage, making the mine less visible. It may be possible by examining the fouling on a derelict mine to determine its point of origin and the time it has been submerged or afloat. The accumulation of slime and fouling on metallic surfaces may protect them from the erosive effects of sea water at high velocity.

These and other similar phenomena are discussed in the present chapter.

THE FOULING OF SHIPS

The fouling of ships results in a reduction of speed, an increased cost in fuel, and losses in time and money in applying the necessary remedial measures. The immediate effect is due to an increase in the resistance to movement of the hull through the water—a phenomenon known as frictional resistance. Since frictional resistance is the basic phenomenon on which the most important aspects of the fouling problem depend, and since it is a matter of some intricacy, the technicalities of the subject are treated in the following chapter, which summarizes some of the more comprehensive experimental data available. For present purposes, it will serve to point out that the accumulation of fouling may readily reduce the

speed of the ship by several knots; and in the case of war vessels and other types of ships in which extreme speed is essential, its occurrence may result in the loss of advantages for which great sacrifice has been made.

As the result of experience over a number of years, the British Admiralty makes an allowance for design purposes for an increase of frictional resistance of $\frac{1}{4}$ per cent per day out of dock in temperate waters and of $\frac{1}{2}$ per cent per day in tropical waters. The result of this assumed rate on speed and fuel consumption at the end of six months for various types of ships in temperate waters is given in Table 1. In tropical waters such results would be expected at the end of three months (20). In the United States Navy the Rules for Engineering Competition in effect prior to the war allowed for 3 per cent increase in fuel consumption per month (3).

TABLE 1. Effect of Fouling after Six Months out of Dock in Temperate Waters

(Frictional resistance assumed to increase $\frac{1}{4}$ per cent per day)

Type of Ship	Standard Displacement Tons	Loss of Maximum Speed Knots	Percentage Increase in Fuel Consumption* to Maintain a Speed of	
			10 Knots	20 Knots
Battleship	35,000	1½	45	40
Aircraft carrier	23,000	1½	45	40
Cruiser	10,000	1¼	50	45
Destroyer	1,850	2	50	35

* These figures are based on the fuel consumptions for propulsion only, i.e. auxiliaries are not included.

Naturally these effects will depend not only on the waters in which the ships operate but also upon the efficiency of the antifouling paints employed. Since the British Admiralty utilizes paints which are obtained from a variety of manufacturers, it seems probable that the estimations given in Table 1 are applicable to vessels coated with the commercially available paints. Great improvements have been made in the coatings employed by the United States Navy, and it is reported that during the recent war in the Pacific it was found unnecessary to make allowances for fouling in estimating fuel requirements.

In addition to the direct expense of the increased fuel consumption required to drive a fouled ship at a given speed and the increased wear and tear on machinery which this may entail, the expense of docking the vessel periodically for cleaning the

bottom is great. The cost of placing a vessel in dry dock or on a marine railway, cleaning, and painting the bottom varies from $1,000 to $15,000, de-

Visscher stated in 1928 that these costs in the case of a large vessel such as the *Leviathan* or *Majestic* were approximately $100,000 (*35*). This estimate
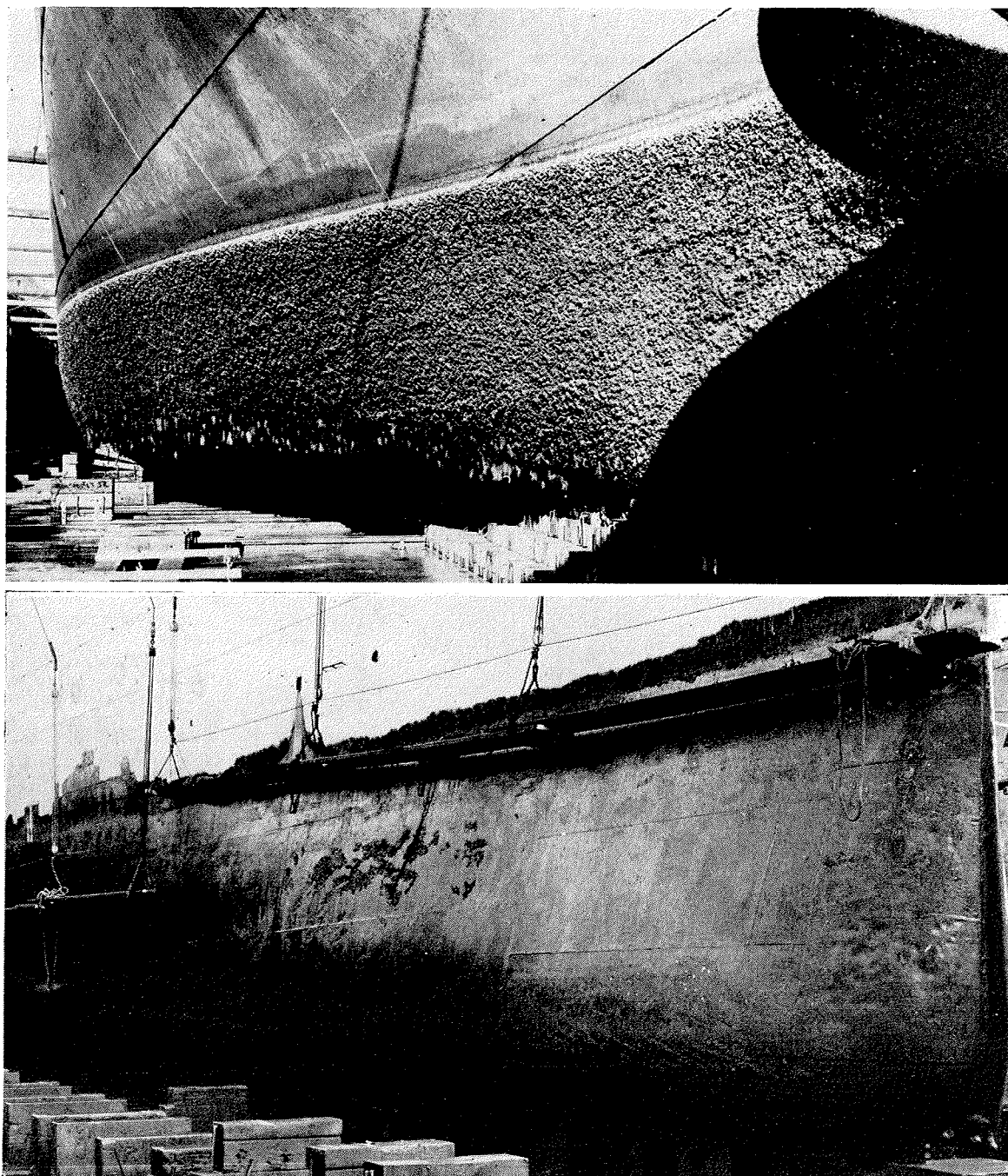

FIGURE 1. *Above:* U.S.S. *Tippecanoe*. Painted with Navy formula 15RC. Twelve months waterborne. (*Below*): U.S.S. *Augusta*. Painted with Navy hot plastic antifouling paint. Twenty-eight months waterborne. Official U. S. Navy photographs.

pending on the size of the vessel, according to Adamson (*1*). The charges incurred by an 18,000-ton passenger liner, docked during 1940 in the San Francisco area, amounted to $4,400. This ship is docked and repainted every nine months (*4*).

did not include the loss of income incurred during the period while the ship was out of service. The time spent in dry dock varies from three days to three weeks or more. For a group of over 200 ships listed by Visscher the average is seven or eight

days. Visscher stated that over $100,000,000 was spent annually by United States shipping interests alone, because of fouling.

Any improvement in the technology of protecting ships from fouling which permits the extension of the period between dockings will lead to important savings in time and expense. Prior to the war, vessels assigned to operating units of the fleet were docked for underwater painting at intervals of approximately nine months (18). Under wartime conditions the activity of the ships was so great and they were docked so frequently that little time was lost for the sake of maintaining the bottoms in good condition. Under peacetime conditions, naval vessels spend a large part of their time in port, where they are subject to severe fouling. Improvements in the antifouling coatings which prolong the period between dockings will lead to substantial savings. This is true also of commercial vessels, especially freighters which may spend considerable periods in port.

The improved protection provided by modern paints is illustrated by Figures 1 and 2. Figure 1 (above) shows the heavy fouling which developed in twelve months on a ship coated with the prewar standard antifouling paint 15RC. A ship protected with the modern hot plastic coating, which remained practically clean while waterborne twenty-eight months, is shown for comparison below. Figure 2 shows the clean condition of a patch of modern hot plastic paint in comparison to the fouling developed in seventeen months on the remainder of the hull which was painted with the older formulation.

The improvement in protective coatings for ships' bottoms due to recent work by the Bureau of Ships has led to the following accomplishments:

a. Vessels can remain out of dry dock as long as eighteen months with inconsequential reduction in speed or increase in fuel consumption due to fouling. It is consequently unnecessary to dock ships more frequently for painting than is required for repairs to hull and submerged fittings.

b. Dry docks have been more available for battle damage repairs due to the reduced routine docking load.

c. The demands for fuel by the fleet are perhaps 10 per cent less than formerly.

d. Fewer tankers are needed to service the fleet.

e. The corrosion of ships' hulls is noticeably reduced.

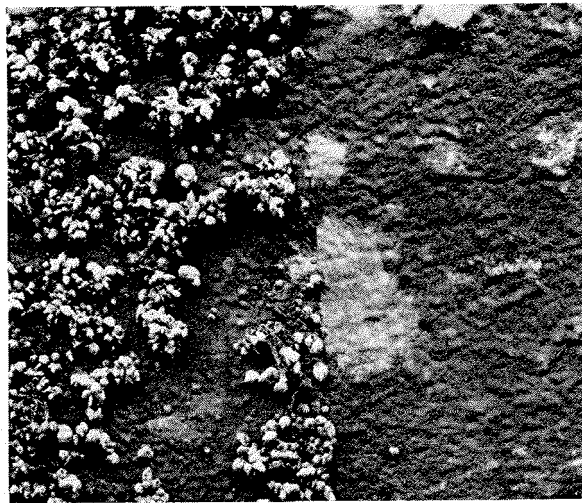A variety of additional savings in time and money have been realized by improvements in the

FIGURE 2. Comparison of fouling on old Navy formulation 15RC (*left*), and modern hot plastic antifouling paint (*right*), after 17 months waterborne. Official U. S. Navy photograph.

technology of the manufacture of paints and the preparation of the hull for painting (14).

The tendency of ships to foul is related to the type of service in which they are employed, and, particularly, to the resulting time spent in port. This follows from the fact discussed in Chapter 13 that the larvae of many fouling organisms have difficulty in attaching to submerged surfaces when the velocity of the water across the surface exceeds about one knot. At greater speeds than this, the growth of some organisms previously attached is also supressed, particularly if they have not been long established, and at high speeds the attached organisms may be washed away bodily.

Visscher has made an analysis of the relation of the duty of ships to fouling, based on the study of 217 vessels (35). The relation of the degree of fouling to the period spent in port is shown in Figure 3.

The time spent in port is naturally related to the purpose and duty of the ship. The tendency of
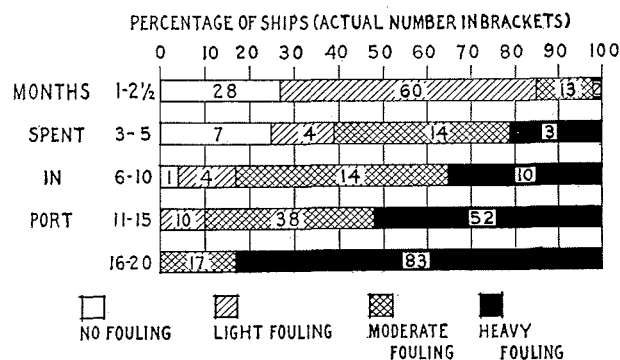

FIGURE 3. Relation between the degree of fouling and the amount of time spent in port between dry dockings. From Visscher (35).

ships of different types to foul is illustrated in Figure 4. Passenger vessels appear less liable to foul than freighters, as might be expected from their more active service and greater speed. Among naval vessels, destroyers and cruisers have
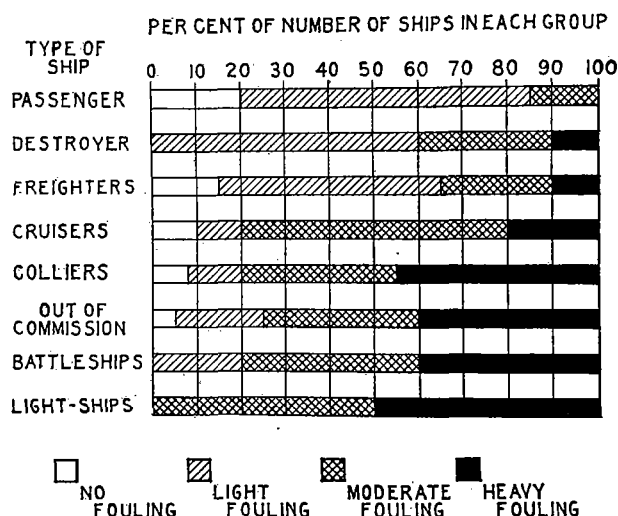

PER CENT OF NUMBER OF SHIPS IN EACH GROUP

FIGURE 4. Relation between type and duty of ship and the amount of fouling, disregarding the factor of time. From Visscher (*35*).

a greater immunity than carriers and battleships, which, in time of peace, like ships out of commission and lightships, spend the greater portion of their time moored or at dock.

The time required for ships to foul depends on the efficacy of the protective coating, which is sooner or later destroyed either by the solvent action of sea water, the physical breakdown of the paint film, or by corrosion. After the paint is damaged, fouling may develop rapidly and cover the unprotected surface completely within a few weeks. It is estimated that as much as 200 tons of fouling may be removed from a ship's bottom at a single docking (*1*).

Few of the ships examined by Visscher remained clean for a period longer than nine months, and all became at least moderately fouled by the end of sixteen to eighteen months, as may be seen from Figure 5. These data are based on ships protected with the paints available some twenty years ago. There is little doubt that ships with the better coatings now available would show a substantial improvement.

The tendency to foul varies greatly with the waters in which ships ply. Fouling can attach only at such times as the organisms are infecting the water with their zoospores or larvae. Its growth varies with the temperature of the water. These biological phenomena are discussed in detail in

subsequent chapters. It is generally considered that fouling is most severe in tropical waters, where growth is rapid and where there is little seasonal interruption of the reproductive processes. In temperate latitudes heavy fouling may occur in summer, but during the cold winter period little growth develops.

In fresh water few fouling organisms occur and these are chiefly plants which attach close to the water line. Ships which can be moored in fresh water consequently enjoy a partial immunity. It is sometimes suggested that vessels should be taken into fresh water to kill off the fouling. This is only a partial measure, since the shells of barnacles and some other fouling organisms are firmly attached and adhere to the bottom even though their occupants are dead.

The only method of preventing fouling which is successful with modern ships is the use of toxic paints. Because of biological considerations the demands put on such paints differ from time to time and from place to place, and different coatings have sometimes been proposed for ships in various services. Vessels used in temperate waters, subject to fouling for only a part of each year, may be protected adequately with a relatively poor paint, effective for only six or eight months, provided they are docked annually and start the fouling season with a fresh coating. Little is to be
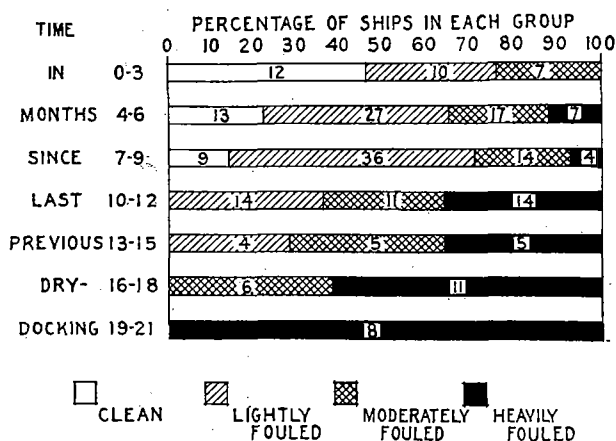

FIGURE 5. Relation between amount of fouling and amount of time between dry dockings. From Visscher (*35*).

gained by such economies, however, since the cost of the coating is only a small part of the expense of docking and repainting. Effective paints are not necessarily expensive paints. A paint which is effective under the most severe conditions of fouling will be effective in preventing growth under any condition. The superior underwater coatings now

used by the Navy have been developed in response to a demand for paints which would completely prevent the growth of fouling *under the most severe conditions* and for the greatest possible period.

NAVIGATION BUOYS

Moored structures such as buoys are even more subject to fouling than ships, since they remain permanently in coastal waters where fouling organisms abound, and since the fouling is not washed away by rapid motion through the water. The tidal currents to which such structures are often exposed appear to favor the growth of the fouling, which finds an opportunity to attach during periods of slack water even where the currents are strong.

The population which grows on moored structures is frequently different from that observed on ships. It contains a larger proportion of mussels and the soft-bodied forms liable to be removed from ships at high speed. In temperate waters, mussels constitute the major fouling on buoys, although these shellfish are not usually observed on ships unless they lie idle in harbor.

Navigation buoys, even though sometimes protected by antifouling paint, usually foul heavily before servicing, which in normal times takes place at yearly intervals. (See Figure 6.) The moor-

FIGURE 6. Navigation buoy heavily fouled with mussels and *Laminaria*.

ing chains cannot be protected with paint. The rate at which fouling accumulates depends upon the kind of organisms present and on the temperature of the water. In the case of fouling by mussels, rather satisfactory predictions of the rate of accumulation can be made from a knowledge of the

seasonal variation in temperature, as discussed in Chapter 6.

Mussels have been observed to accumulate at a rate of one pound per square foot of surface per month, and barnacles at about half this rate. The
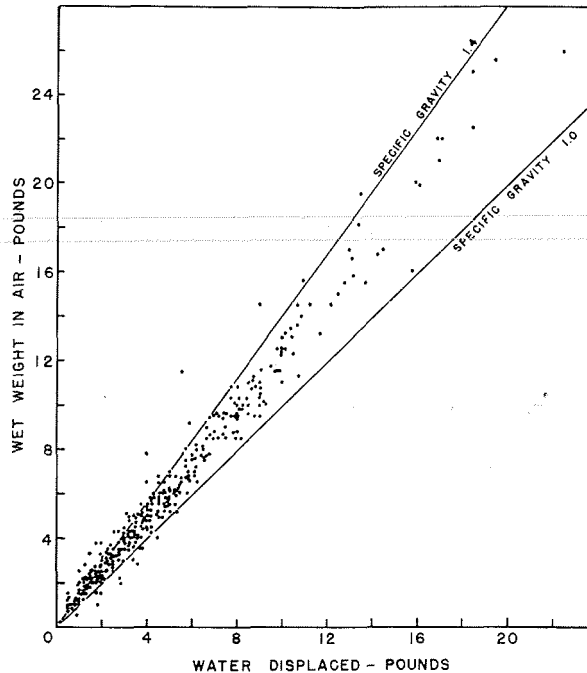

FIGURE 7. Relation of weight to displacement of fouling from navigation buoys of United States coastal waters.

maximum accumulation of fouling which has been recorded from navigation buoys is about 25 pounds per square foot on a buoy which had been set in the Woods Hole region for 35 months. Another buoy set in the same area for 31 months had as much as 40 pounds per linear foot of 2-inch chain (*12*). In the case of barnacles, the maximum accumulation recorded amounted to $6\frac{1}{4}$ pounds per square foot on a buoy set for a year at Anacapa Island.

The data given above represent the weight of fouling as measured in air. Under water the weight is less and depends upon the density of the fouling material relative to that of water, i.e., upon its specific gravity. The specific gravity can be measured in a number of ways. Rather different results are obtained, depending on the degree to which the fouling is dried before weighing. Weights of wet fouling measured in air generally include some water retained in the shells of mussels, oysters, and similar forms, whose displacements also vary depending on whether they are closed or open. Figure 7 shows the ratio between wet weight in air and weight of water displaced for a large

number of samples of fouling from buoys of United States coastal waters, and adequately represents all commonly encountered types of fouling except that dominated by oysters. A specific gravity of 1.4 seems to be a proper allowance for engineering estimates. The total weight will depend, of course on the locality and duration of exposure. Separate measurements of various fouling organisms show that only shelled forms have any significant weight under water. Mussel fouling has a specific gravity of about 1.3; acorn barnacles and rock oysters
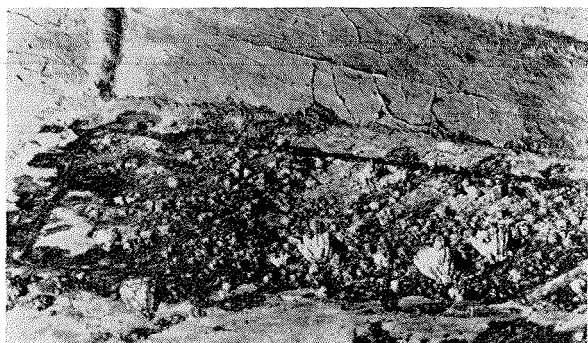

FIGURE 8. Fathometer plate, fouled with barnacles. Official U. S. Navy photograph.

average slightly higher. Hydroids and tunicates, on the other hand, displaced almost exactly their weight in air, and have almost no weight under water (11).

Fouling on buoys is more or less uniform in type and amount in a coastal zone which sometimes extends many miles offshore. On the Atlantic coast of the United States the limit of this zone is approximated by the 100-foot depth contour. It has been suggested that this depth marks the limit of extensive natural beds of such fouling organisms as mussels which serve as the source of infection for the buoys (13). Local currents and other factors may modify this accessibility of the buoys to natural sources of fouling. Beyond the 100-foot contour, fouling decreases and the characteristic population changes, mussels and acorn barnacles, for example, being replaced by goose barnacles.

Fouling on buoy installations has been found at all depths examined, the maximum being some 450 feet. Below 100 feet, hydroids are the characteristic dominant forms. The only part not fouled is the lower 10 or 20 feet of the mooring chain, which is chafed and abraded by dragging on the bottom and is possibly subject to scouring by silt carried by bottom currents. The anchors themselves are often fouled, when not buried, as are cables and other structures on the bottom. Except for differences occasioned by the vertical zonation of par-

ticular species, the buoy installations show no consistent change in amount of fouling with depth. This is contradictory to many reports and opinions, but is based on extensive and reliable evidence. Most of the observations, however, are of buoys set in channels and other inshore local deeps. Toward the edge of the continental shelf, where deep water is general, collections from a few buoys indicate that fouling may be limited essentially to goose barnacles at the surface and to a mixture of other forms on gear at the bottom. Buoys set in harbors often have a different fouling population from those set offshore. Dense growths of tunicates, bryozoans, and other soft forms frequently predominate.

Navigation buoys ordinarily have sufficient reserve buoyancy so that the weight of fouling is quite unimportant. Its chief harmful consequence is the nuisance of cleaning the buoy and chain prior to repainting. The internal tubes of whistling buoys sometimes foul heavily and this impairs their proper functioning.

UNDERWATER SOUND EQUIPMENT

Commercial vessels are commonly equipped with sonic sounding devices; naval vessels are equipped with more specialized instruments for producing and detecting underwater sounds. These and the similar acoustic devices permanently installed under water for purposes of coastal defense are not usually protected with antifouling paint nor are they constructed of metals which resist fouling. Their usefulness may be seriously impaired as the result of the accumulation of fouling on the surfaces which transmit sound. (See Figure 8.)

The fouling which occurs on sound equipment is similar to that of ships' bottoms. Barnacles, tube worms, tunicates, hydroids, and bryozoa are the chief offenders. Algae are relatively unimportant because the installation is commonly located too far below the surface to favor plant growth. In a survey of the condition on naval vessels recently made by the Naval Research Laboratory few sound domes were found free of fouling (9). Barnacles were rarely absent even from ships which were docked at short intervals or were cruising in northern waters. Tube worms were characteristic on ships from the South Pacific. Heavy fouling, sometimes ½-inch thick, was present at times. The heaviest fouling occurred in the tropical waters of the South Pacific, Mediterranean, and Caribbean Seas.

Since fouling organisms cannot attach on rap-

idly moving surfaces, and since their growth is inhibited or they may be torn free by water currents of high velocity, fouling is especially prevalent on ships lying to for long periods, on training school ships and barges, and on stationary installations.

On the outside of sound domes, fouling is greatest on the nose and tail where the velocity of flow is least during the motion of the ship. It also occurs on the projector, retracting shaft, and sound well. (See Figure 9.) In some cases the dome can not be retracted because of the growth. In free-flooded equipment it is found on the inside of the dome where the quiet water encourages the growth of soft-bodied types of fouling as well as the hard-shelled forms. These often accumulate in the bottom of the dome to a substantial thickness. These difficulties might be eliminated by abandoning the free-flooding feature.

In the Caribbean, dry-docking is often required within two or three months because the sound equipment is rendered inoperative by fouling. While field studies have not been made to determine quantitatively the effect of fouling on the ranges over which sound equipment is effective, theoretical considerations and practical tests leave little doubt that the efficiency of sound gear may suffer seriously.

The decrease in sound transmission through a sound dome due to fouling may be attributed almost entirely to reflection, scattering, and absorption.

When sound waves impinge on a submerged steel plate, part of the sound is transmitted through the plate and part is reflected. The reflected component becomes greater as the plate thickness increases. The calcareous and siliceous shells of the fouling organisms, having a higher density and modulus of elasticity than water, act to increase the effective thickness of the dome wall and thus increase the reflection and decrease the transmission.

The presence of bubbles in water greatly increases the absorption and scattering of sound energy. Absorption of sound by bubbles is very great if their size is near to the resonant size of the particular sound frequency. For example, the resonant size at 25 KC is 0.2 mm., and if 10 bubbles of this size are present per cubic foot, the attenuation will be 100 decibels per kiloyard. Fouling growths may be expected to entrap free bubbles from the surrounding water.

The attenuation through sound domes due to these effects becomes enhanced in echo-ranging

and depth-sounding equipment, since both the outgoing and reflected sound must pass through the dome. For example, if fouling decreased the transmission by 30 per cent, the echo intensity would be reduced by one-half.

Fouling may also decrease the effectiveness of sound gear by increasing cavitation noise. This is sound which results from disturbances in the normal streamlined flow around the sound dome when
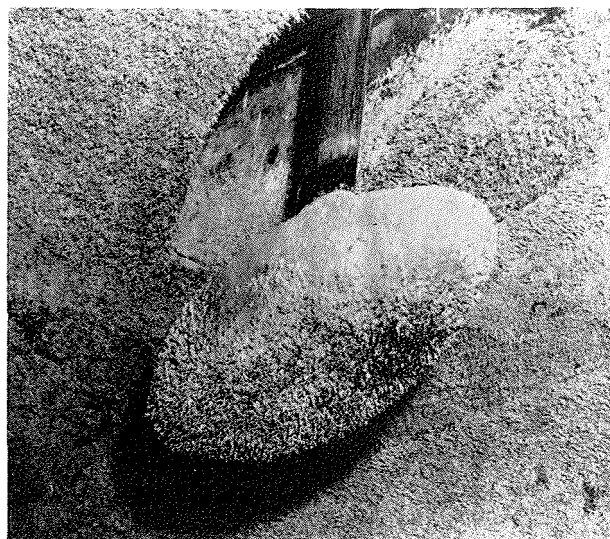

FIGURE 9. Retractable sound dome showing fouling on projector and sides of sound well. Official U. S. Navy photograph.

the ship is under way. It interferes with the use of sound equipment in a way somewhat different from the two phenomena described above. Whereas these actually decrease the strength of the signal being transmitted or received by the gear, cavitation produces a background of noise which makes it difficult to recognize the received signal. While quantitative noise measurements from fouled sound domes are unavailable, several cases have been reported where excessive water noise at relatively low speed was attributable to barnacles attached to the sound window. In one such case, excessive noise at a certain bearing disappeared after the ship was dry-docked and a large barnacle at that bearing was removed.

The effects of fouling on sound transmission are discussed in some theoretical detail in a report by Fitzgerald, Davis, and Hurdle (9).

An experimental study of the effects of fouling and of applications of antifouling paint on sound transmission has been made by the Naval Research Laboratory. Steel panels 0.060 inch by 30 inches by 30 inches were exposed to severe fouling at Miami Beach, and measurements were made of the transmitted energy as fouling pro-

gressed. The results are shown in Figure 10. The unprotected plate became covered with barnacles. bryozoa, tunicates, hydroids, and algae, with the soft-bodied forms predominating. At the end of 165 days it had built up a mat one inch thick. At this
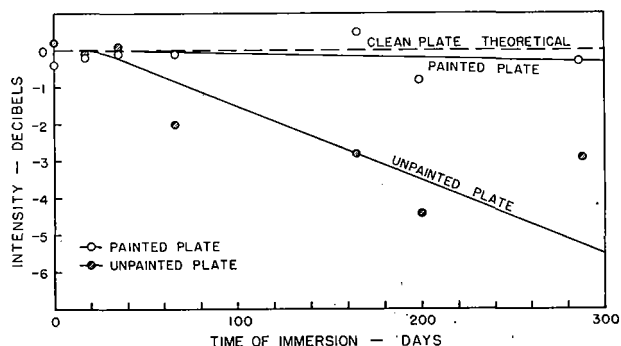

Figure 10. Intensity of sound transmitted by a steel panel 0.060 inch thick as affected by fouling during immersion. After Fitzgerald, Davis, and Hurdle (*9*).

time it caused an attenuation of 3 decibels; after 300 days the attenuation was 5½ decibels. This means that only 50 per cent and 25 per cent respectively of the incident energy was being transmitted. In contrast, at the end of 300 days, the attenuation of a plate coated with antifouling

paint was only 0.5 decibel, corresponding to about 90 per cent transmission.

By comparing the fraction of the incident energy transmitted with that reflected by the fouled plate when placed at an angle of 45° with the incident beam, and correcting for the effects produced by a similar unfouled plate, it was possible to estimate the relative importance of reflection and absorption in the transmission loss due to the fouling.

TABLE 2. Per Cent Transmission, Reflection and Absorption of Sound of 24.3 kc/sec Due to Fouling on Steel Panels Immersed 165 Days

		Trans- mission	Reflec- tion	Absorp- tion
Clean panel	A	79.9	19.3	0.8
Clean panel	B	81.2	18.2	0.7
Fouled panel	A	28.2	6.3	65.5
Fouled panel	B	28.2	7.9	63.9
Painted* panel	A	79.9	12.9	7.6
Painted* panel	B	79.4	12.9	8.0

* Coated with Navy Aeronautical Specification M-55g.

The results, given in Table 2, show that practically all the energy loss is due to absorption.

Fouling not only affects sound gear by reducing the intensity of the transmitted sound, but also

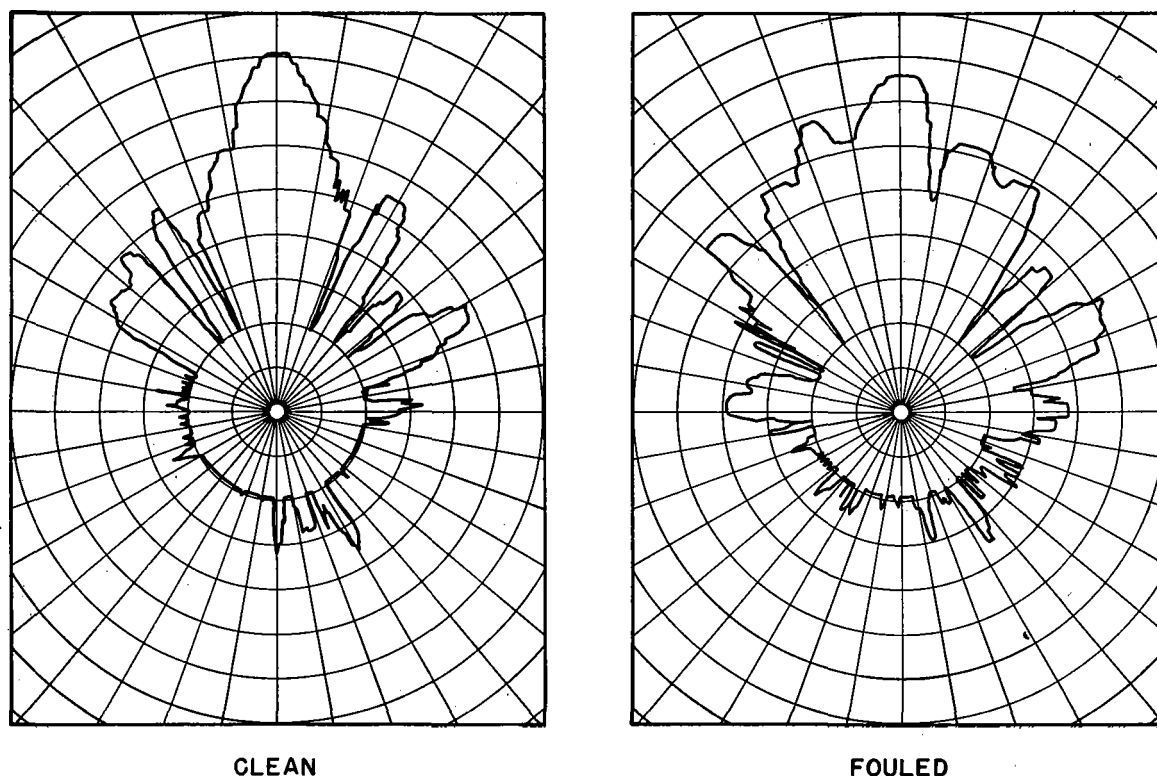## PROJECTOR   BEAM   PATTERNS

CLEAN

FOULED

Figure 11. Beam pattern of a projector measured when clean and after the growth of fouling in which mussels predominated. After Fitzgerald, Davis, and Hurdle (*9*).

modifies the field pattern of a projector. Figure 11 shows the field pattern of a projector measured before and after the accumulation of a heavy growth in which mussels predominated.

Underwater sound equipment tends to foul because the exposed surfaces are usually constructed of metals which do not resist fouling, or because, if toxic materials such as copper or its alloys are employed, they are inactivated by galvanic effects resulting from coupling with iron structures. Usually the surfaces of sound equipment are not protected with antifouling paint, either through disregard of the difficulties which may arise from fouling or for fear that the paint coating will interfere with the operation of the equipment.

The effect of coatings of antifouling paint on sound transmission have been studied, using sound varying in frequency. The result, shown in Figure 12, indicates that the use of a special coating developed at the Naval Research Laboratory for the purpose produces no essential change in the sound

FIGURE 13. Growth of tube worms in a ship's 4-inch fire main. Official U. S. Navy photograph.
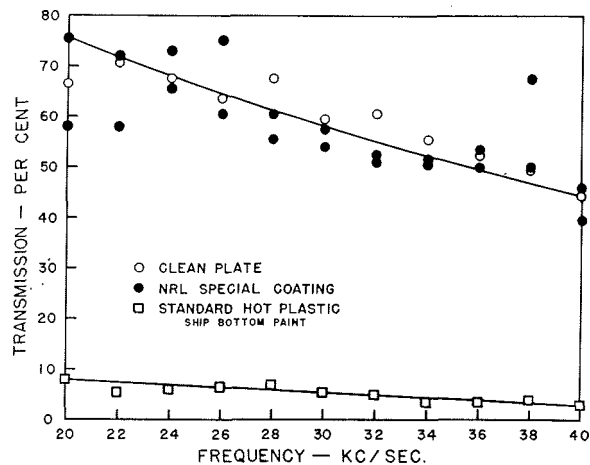

FIGURE 12. Transmission of sound of varying frequency through steel plates, uncoated, painted with a special coating (Navy Aeronautical specification M-559) and with standard hot plastic shipbottom paint. After Fitzgerald, Davis, and Hurdle (9).

transmission of a steel panel. The standard hot plastic shipbottom paint, on the other hand, reduces the sound transmission very greatly. This effect is attributed to the presence of air occluded in the coating.

SALT WATER PIPE SYSTEMS

Pipes and conduits used to distribute salt water in vessels, industrial plants, and aquaria provide favorable places for fouling organisms to grow. Flow is interfered with due to the decreased size of the channel and the increased roughness of the surface. There is always danger that the systems
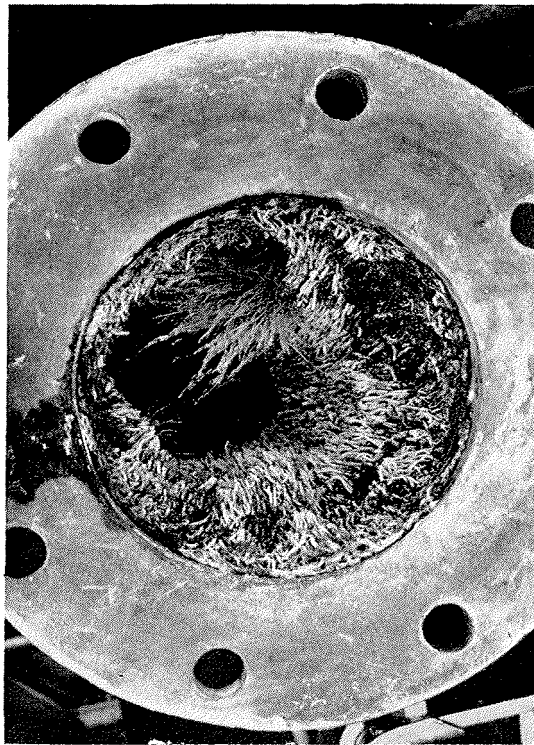
will be blocked at valves, orifices, and other constricted places by organisms which become detached.

The problem is particularly acute in the case of ships, because the piping is designed for high velocities and is relatively small, so that fouling may greatly reduce the capacity. It is essential that the pipes be kept free from fouling at all times because of the hazard from fire if the fire mains become clogged. Because of the complexity of the systems, the expense of breaking them down for cleaning is great.

It has been found that fouling occurs most readily in fire mains and in branches leading to fire plugs on deck, ice machines, and other auxiliary machinery. A section of four-inch fire main almost completely clogged with tube worms following a period of duty of the ship in the tropical Pacific is illustrated in Figure 13. The fouling is more pronounced in the sections of five inches or more in diameter, and in the vicinity of boiler and engine rooms where the temperature is usually higher. It is reported by ship personnel that where the temperature is from 70° to 100°F, growth is prevalent, with the greatest concentration between 80° and 90°F. At higher temperatures, the amount of fouling diminishes, and it is nonexistent where the water temperature is maintained at 150°F.

The intensity of fouling also diminishes greatly at temperatures below 60°F. A pipe having constant flow will usually be free of growth, while one with very little flow, or where the water comes to rest for short periods, will be badly fouled.

The fouling of ships' piping depends upon the local conditions of operation, and may be particularly severe in the tropics. Troublesome growth was reported from Galveston and Hawaii. At the

any part of the iron structure of the ship will tend to inactivate certain parts of the internal surface of the pipe, even though it be constructed of copper, unless sections of insulating material are introduced at this point.

Currently, experiments are being made in coating the insides of the pipe systems with antifouling paints similar to those used on ships' bottoms (*19*). These experiments are promising and have shown
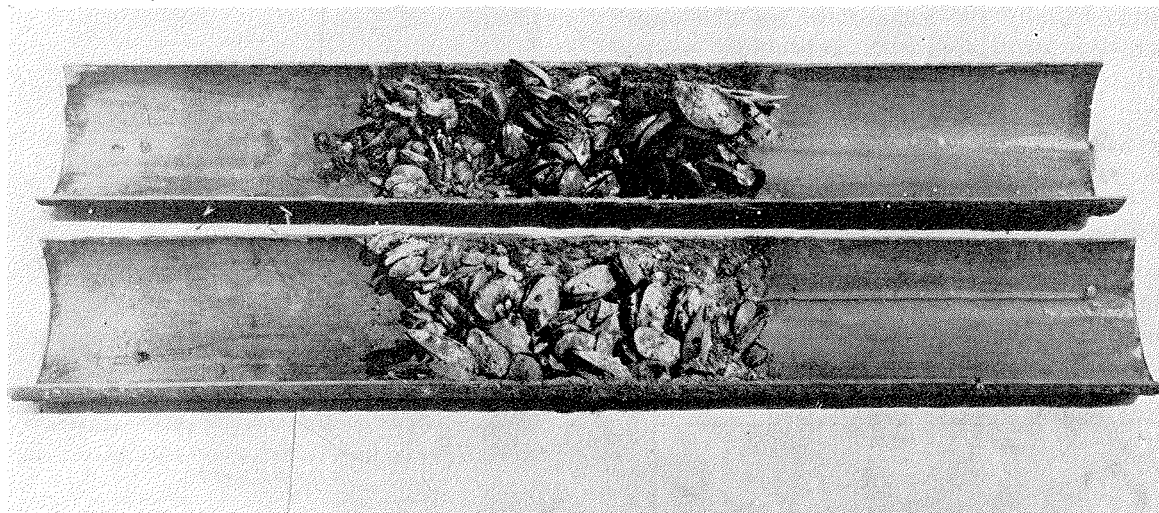

FIGURE 14. Section of pipe laid open to show a plug of mussels which developed at a point where the protective coating of antifouling paint had been damaged during welding of a joint.

latter district it was necessary to clean the condenser tubes every eighteen days. At Panama no fouling occurred, presumably because the tender was stationed in the fresh water of Gatun Lake at regular periods. In the New England area, severe fouling with mussels has been reported.

Copper tubing is frequently used in vessels to conduct salt water and is apparently not prone to foul. Its tendency to erode, however, has led to the use of lead-lined steel pipe, galvanized wrought-iron and steel pipe, and copper-nickel alloy tubing as a substitute in American naval vessels. Marine growths have been found in all of these systems, the more severe cases reported being in the lead-lined and galvanized iron pipes.

The prevention of fouling in salt water pipes by the use of suitable metals is difficult, since those metals which resist erosion adequately do not have antifouling surfaces. The most satisfactory compromise at present available is 70–30 copper-nickel. It is possible that the bronze couplings, flanges, and fittings connecting adjoining sections of copper-nickel pipe may produce galvanic effects sufficient to increase the tendency of the copper-nickel pipe to foul. The coupling of the pipe with

that protection may be afforded in this way. It is not known as yet, however, how permanent this protection will be. Difficulties may arise from the chipping off of parts of the paint surface, which might give trouble should the chips ultimately lodge in fire sprinklers or other critical places. Localized damage of the paint coating may also cause accelerated corrosion of iron piping at the points were the metal is exposed. Figure 14 shows a length of pipe which had been protected by painting laid open. The pipe is free of fouling except at a point where the paint had been damaged in the course of welding a joint. At this point a heavy plug of mussels has developed.

Another possible method of preventing the fouling in salt water pipe systems is the injection of chemicals designed to sterilize the water, much as is done with domestic water supplies. The machinery developed for the latter purpose might be adapted for use on shipboard.

Chlorine has been used successfully to prevent the growth of marine organisms in the sea water service lines of industrial plants (*6*). Experiments have indicated that residual chlorine concentrations as low as 0.25 p.p.m. completely prevent

fouling in flowing salt water lines. Unfortunately, the quantities of water circulated through a ship are so large that treatment to even this small concentration is difficult. The use of compressed chlorine gas on shipboard is prohibited. Electrolytic generation of chlorine requires bulky equipment and presents other technical difficulties. The use of chemical sources such as calcium hypochlorite involves a considerable storage and maintenance problem. Finally it has been found that even these small concentrations of chlorine greatly increase the corrosion of steel piping (34). Such corrosive effects are thought to be due to the elimination of protective coatings of slime by the chlorine, rather than to any direct chemical effect by the small concentrations of chlorine.

Experiments have indicated that sodium pentachlorphenate, sold under various trade names such as Santobrite and Dowicide, might be preferable to chlorine for use on shipboard. The introduction of sodium pentachlorphenol in concentrations of 1 p.p.m. completely prevented the fouling of steel pipes, without increasing the rate of corrosion. Recent tests conducted in collaboration with the Boston Navy Yard have led to the development of suitable equipment for treating salt water lines of vessels with this material. A product sold as Nalco 21 M has sufficient solubility in sea water to be adapted to the purpose. The chief disadvantage is the added maintenance and supply problem, and the irritating character of the material, which must be handled with some care.

Power stations, oil refineries, and other users of sea water for industrial purposes may be greatly inconvenienced by the growth of fouling organisms in their water circuits. The growth reduces the carrying capacity of the conduits by increasing the frictional resistance as well as by reducing the pipe line diameter. The growth of sponges in a 60-inch pipe has been known to reduce the Hazen Williams coefficient by 35 per cent. The growths continue to accumulate until they are so great that they may be torn loose and swept into screens, tube sheets, or pumps. The resultant stoppage may allow pressures to accumulate in the systems to the breaking point. When used for fire service, the sudden rush of water has loosened the fouling which has blocked valves, hydrants, and nozzles, and even completely shut off the water supply with disastrous results (6).

In addition to the inefficiencies of operation and the hazards caused by fouling growths, expense arises from the necessity of closing down parts of the system for cleaning. As much as 266 tons of

shells have been removed in one year from the tunnel of one New England power station. At another tunnel, dead shells have accumulated to a depth of 3 to 6 feet (6). Many stations have had to shut down entire turbo-generator units two or three times a day to permit removal of shells blanketing the tube sheets. Shells which enter the tubes cause high impingement velocities which increase erosion and reduce tube life (32).
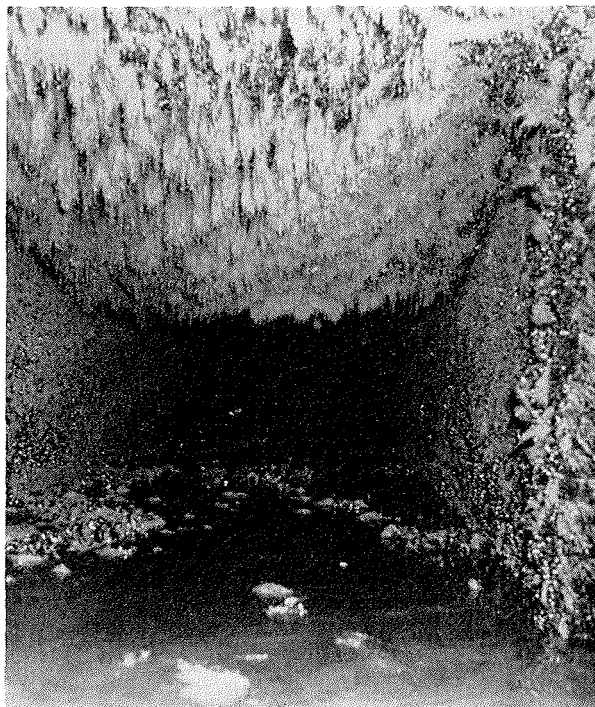

FIGURE 15. Fouling developed in less than four months in intake tunnel of the Lynn Gas and Electric Company.

The growth encrusting the walls of the intake tunnel of the Lynn Gas and Electric Company less than four months after cleaning is illustrated in Figure 15. The mussels growing on the wall of this tunnel weighed more than 10 pounds per square foot and made a mat 2 inches thick.

In addition to the mechanical effects produced by the growth of macroscopic fouling organisms, the accumulation of deposits due to capsulated and slime-forming bacteria reduces the heat-transfer efficiency of condensers (7, 21, 22).

The animals which cause trouble in conduits are those which predominate in the fouling of sheltered waters, i.e., hydroids, bryozoa, mussels, and tunicates. The mussel, *Mytilus edulis*, is the most important form in salt water circuits in temperate latitudes. The scallop, *Pecten latiauratus*, is troublesome in warmer waters. Bryozoans, sponges, and in Europe the mussel, *Dreissensia*

polymorpha, are responsible for blocking fresh water lines. The algae give little trouble except in sunlit portions of the installations.

Numerous methods have been suggested for preventing the fouling of industrial circuits, but few meet the essential requirements of being economical to install and operate, and of effectively eliminating the fouling without interrupting the operation of the plant.

Screens fine enough to exclude the larvae are impractical because they clog too readily with silt and detritus.

The organisms could be killed by suffocation only by shutting down frequently and allowing the water to stagnate until its oxygen content is exhausted.

High water velocities might be employed effectively to reduce fouling where such velocities can be maintained without undue cost of pumping, but fouling might still occur if temporary interruptions or localized areas of reduced velocity permitted the attachment of larvae. Fouling so established would be in danger of being torn loose and swept into critical structures such as pumps or condensers unless these were protected by suitable catch basins.

Fresh water might be used to kill off the organisms of salt water circuits, but this would be effective only if the treatment were continued for some time, since many shelled forms such as the mussel can resist adverse conditions by closing their shells. The remains of fouling killed in this way would be apt to clog critical structures.

Antifouling paints cannot be economically applied because they must be renewed frequently. In addition to the cost of their application and the shutdown time required, it would be very difficult to secure a sufficiently clean and dry surface for the successful renewal of the coatings. Some plants have used coal-oil, gas-oil-drip, kerosene, and similar oily products for control. Some control is obtained above the low water level, since the walls become coated with these materials and become unsuited to the attachment of the fouling. No control is obtained below the low water line, however.

The earliest method of control attempted on plant scale was heating the circulating water. The circulating water can be throttled until the desired heat exchange is obtained at the condensers. By reversing the circulation in the system, all parts may be subjected alternately to the heated water. Successful control of mussel fouling was obtained by heating the water to about 90°F for

a period of twelve hours. The treatment must be repeated at monthly intervals during the spawning season to kill the mussels before their shells reach sizes that would be harmful. The cost of operating such a system can be extremely high because of the fuel consumed in heating the water. Installation costs are also increased, because the system and, particularly, the pumps must be designed for reverse flow. It is only for plants having waste heat available that the cost is not prohibitive (*31*).

A variety of methods of controlling fouling by introducing poisonous materials into the water have been attempted or considered. Active poisons such as cyanide are rejected because of the danger to human life. Treatment with sulphuric acid has been tried by a private firm at the Leith Docks and was partially successful, but was abandoned because of the severe corrosion which resulted. To be effective, sulphuric acid must be added in a proportion of 150 p.p.m. so as to reduce the pH to 3. The cost of the acid required is itself prohibitive, irrespective of the corrosive damage.

The most successful and economical method of treatment is with chlorine. Power stations scattered along the Atlantic coast from Massachusetts to Texas have controlled fouling by this means. Although experiments indicate that continuous treatment with chlorine residuals of 0.25 p.p.m. is adequate to prevent fouling, experience at plant scale indicates that residuals of 0.5 to 1.0 p.p.m. are required. Economies can be had by employing intermittent treatment, provided it is frequent enough to prevent larvae which enter the system between applications from developing shells. Adult mussels can close their shells and resist the action of the poison for several days, and prolonged treatment is consequently required when it is desired to kill mussels which have become established. Further economy may be had by omitting the treatment at those seasons when the larvae are absent from the water.

In a 25,000 Kw station, marine fouling can be controlled by the use of chlorine at a cost of about $3.50 per day during the fouling season. More than this amount is saved in increased efficiency of the installation and in the reduction in cost of cleaning (*6*).

DESTRUCTIVE EFFECTS

In addition to interfering with the function of the structures on which it grows, fouling may accelerate the corrosion of their metallic surfaces or

injure the paint coatings intended to protect them from rusting.

It has been argued that a heavy mat of fouling may actually protect the surface from corrosion by preventing the renewed access of sea water or of the oxygen which is required for rusting. This view is supported by the clean appearance of the steel and the absence of red rust when the fouling is scraped away. Friend noted that the shell fauna did not appear to affect corrosion of metals appreciably while living, but that dead organisms stimulated local corrosion, leaving more or less circular patches of damage (10). When individual

but not with calcareous tube worms or algae. LaQue and Clapp did not observe pitting associated with barnacles or bryozoa which were known to be alive, and suggest that it is only when they die that conditions are favorable for excessive pitting. This observation has been confirmed by Mr. C. M. Weiss at Miami. He observed pitting only under the shells of barnacles which were dead, not under the encrusting bryozoa or other forms which grew on the panels.

The pitting frequently shows a radial pattern or concentric rings which reflect the structure and growth characteristic of the barnacle base. Some-
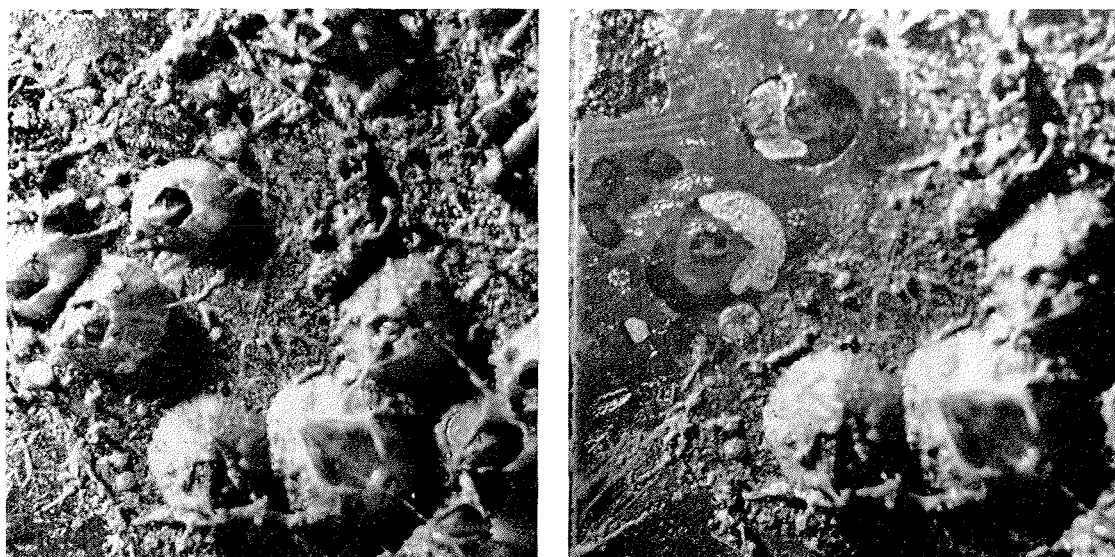

FIGURE 16. Localized corrosion of nickel beneath the bases of barnacles. (*Left*) Fouled condition of the panel after one month's exposure. (*Right*) Pits in the metal revealed by removal of three of the barnacles.

organisms become covered up and smothered by their neighbors, localized corrosion is caused. An example of this action is illustrated in Figure 16. Passive and marginally passive alloys, such as stainless steel and nickel alloys, in which the surrounding surfaces of the metal remain relatively smooth, show particularly clearly the localized corrosion which occurs under fouling organisms.

LaQue and Clapp have observed quite noticeable pitting of nickel-copper alloys within 11 days after the fouling appeared (16). Pits 1.3 mm. deep may develop in 26 days in an alloy containing about 85 per cent nickel and 15 per cent copper. The action is confined to alloys containing 50 per cent copper or less, which foul readily. Unlike most metals the rate of weight loss of these alloys increases during the period of exposure to sea water, a result attributed to the corrosion induced by the fouling. It was observed that these effects were associated with barnacles and filamentous bryozoa,

times the central area stands up as a prominence of uncorroded metal, at other times it is more deeply corroded than the outer area. After the organism has become detached, the pitted area may continue to corrode, with the result that its characteristic pattern is destroyed.

In contrast to these observations, the corrosion of a steel surface may proceed less rapidly under firmly adhering fouling than in the bare areas between the organisms. Figure 17 shows the surface of a steel panel which had become heavily fouled with barnacles. After removing the living barnacles and the corrosion products, the steel surfaces which had been under the bases of the organisms stand out as relatively smooth plateaus surrounded by depressed and pitted areas where corrosion has taken place. This observation shows that the fouling may protect the metal locally. Whether its effect is beneficial or not is uncertain, since it is not known whether corrosion proceeded
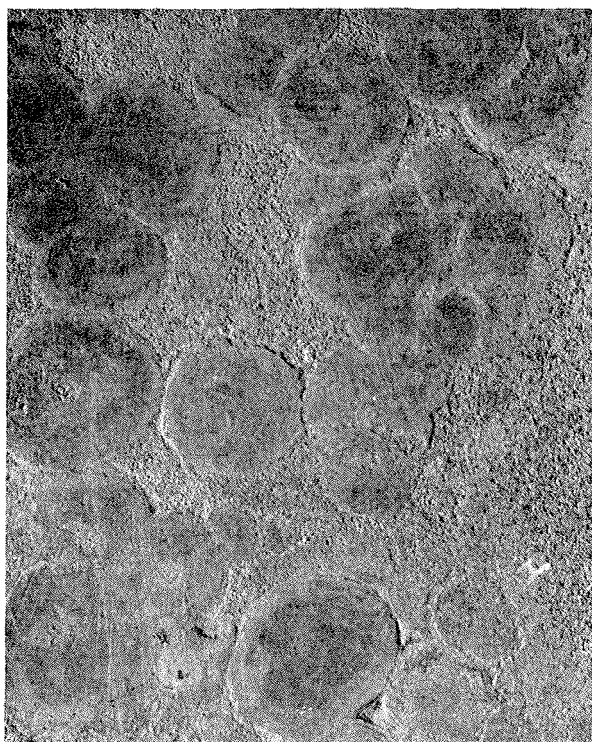
FIGURE 17. Corroded steel plate showing smooth circular areas which had been protected by the bases of barnacles.

more rapidly in the areas between the barnacles than it would have in their absence.

A variety of mechanisms have been suggested to explain how fouling may influence corrosion. One view is that any uneven adherence of the base of a fouling organism may result in inequalities in the concentration of oxygen at the metallic surface, and may create oxygen-concentration cells which accelerate corrosion by galvanic mechanisms. It is also possible that if the greater part of the surface is protected by firmly adhering fouling, any cor-

FIGURE 18. Steel panel showing black deposit which covered steel between the bases of barnacles after three months' exposure in the sea.

rosion due to galvanic effects will be concentrated in the unprotected spaces between the organisms, much as it is in localized breaks in a paint coating, as discussed in Chapter 22. Another suggestion frequently made is that metabolic products of the fouling, and particularly the production of acid conditions and hydrogen sulfide by dying members of the community, create a condition favorable to corrosion (5, 29).

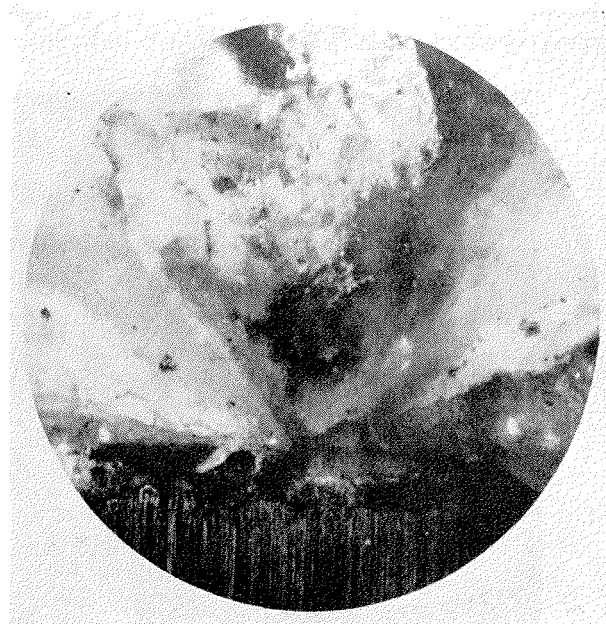The presence of fouling, both alive or dead, may

FIGURE 19. Microscopic section through a paint film showing the wedge shaped edge of barnacle shell plowing into the paint coating. The dark areas are paint; the striated zone at bottom is the steel surface. ×100. Photograph by Dr. F. F. Lucas, Bell Telephone Laboratories.

be expected to favor the accumulation and growth of microorganisms, particularly sulfate-reducing bacteria, to which Legendre (17) has attributed the corrosion of iron under marine conditions. Sulfate-reducing bacteria are known to be active in the destruction of underground pipes. They secure their needed oxygen under anaerobic conditions by reducing sulfates. In this process hydrogen is consumed, and the resulting depolarization of the metallic surface favors its corrosion (36).

Sulfate-reducing bacteria are found abundantly in sea water and in the mud of harbors and on fouled or rusting surfaces which are exposed in such places. The layer of red ferric hydrate which forms on iron rusting in sea water is frequently underlaid by black deposits containing sulfides, which indicates that the primary corrosion products are being formed under anaerobic conditions (33). Figure 18 shows the black deposit which

covered a steel panel between the bases of barnacles after three months' exposure to sea water, and where, as shown in the preceding figure, extensive pitting took place.

Protective coatings intended to prevent the corrosion of submerged metallic structures are frequently injured or destroyed by fouling organisms if the coating does not have antifouling properties. Localized breaks in the coating caused by the fouling lead to serious pitting in these areas, especially if the electrical conditions are favorable to corrosion. This situation has occurred on lock gates and submerged pipe lines (8).

Fouling may injure protective coatings in several different ways. Heavy shelled forms, such as oysters, may become attached so strongly to the

coating that when the shell is torn loose for any cause some of the underlying paint comes away with it. The cementing material which holds the
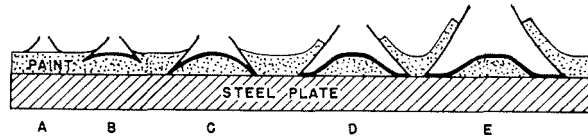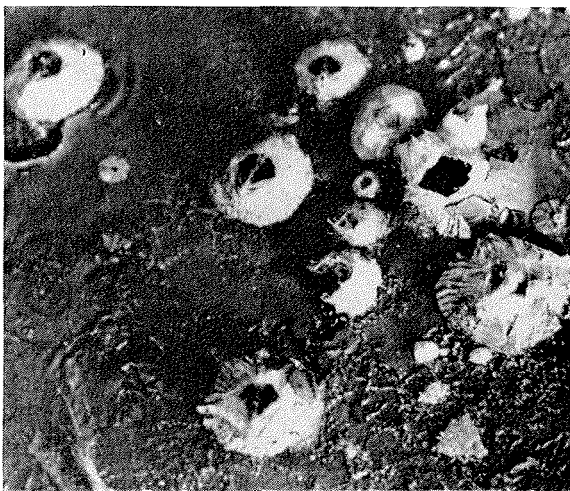

FIGURE 20. Diagram showing how a barnacle plows into the surface of paint. A—Metamorphosed barnacle on paint surface. B and C—The edges of the shell grow downward until checked by the steel plate. D and E—Continued lateral growth forces the paint upward over the barnacle's shell. After Bärenfänger (2).
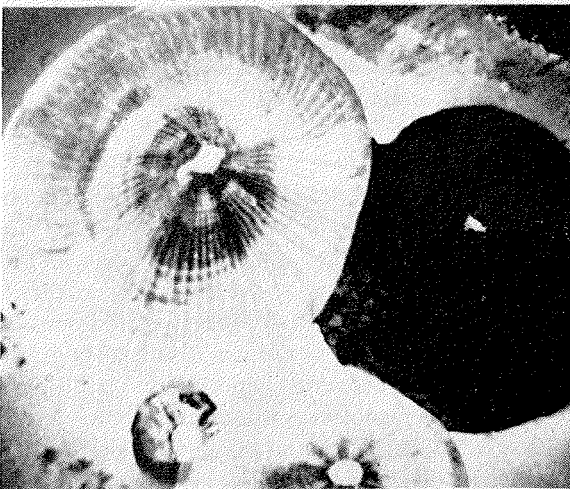
oyster to its substrate appears to have a destructive effect on paint films. If the shell of an oyster attached to a painted panel is carefully dissolved away with acid, the spots where the oyster had

FIGURE 21. A—Barnacles growing on paint, showing chips of paint which have been wedged up by the shell's growth and the marks left by barnacles which have become detached. Photograph by C. M. Weiss. B—Marks left after removing barnacles from a nontoxic paint surface. Photograph from Nelson and Kodet (25). C—Undersurface of a barnacle which has penetrated the paint coating of a glass panel, seen through the glass. The dark circular area is a hole left in the paint by a barnacle which has been detached. Photograph from Nelson and Kodet (25). D—Thiokol coating showing marks left by barnacle bases after removal of the fouling. Photograph by F. L. LaQue.

been attached have a light brown color, suggesting that organic materials contained in the cementing material had penetrated the superficial portion of the paint. The paint film in these brown layers appears to be weakened, for unless great care is taken a thin layer of the paint in these areas tends to peel off, leaving the adjoining paint intact (*25*).

Barnacles may injure paint coatings because of their way of growth (*2, 23, 27, 28*). The growing edge of the shell is sharp, and wedge shaped in

structure of the basal plate can be clearly seen through the glass.

Barnacles may also penetrate certain rubber-like coatings such as Thiokol, as shown in Figure 21D. Coatings of Natural Rubber, Buna S, and Neoprene have not been found to be vulnerable to such damage (*15*).

Soft bituminous coatings may be penetrated by barnacles to a depth of several millimeters. If the barnacle subsequently dies, the exposed surface

FIGURE 22. Effect of fouling on attack by wood borers. Fouling on the block at left was undisturbed during one year's immersion at Miami Beach. The block at its right was cleaned periodically to reduce fouling. The condition of the blocks when split open is shown at right.

section, as shown in Figure 19. As the base enlarges, this edge pushes outward and, if the substrate is not too hard, downward. As a result the edge of the shell tends to plow into the coating and may eventually cut down to the underlying metal. Figure 20 diagrams the process. Figure 21A shows several barnacles which have plowed into an ineffective coating of antifouling paint. The marks left by barnacles leave chips of paint adhering to the outer surface of the shell. The marks left after removing barnacles from a nontoxic paint surface are illustrated in Figure 21B. Figure 21C shows the undersurface of a barnacle which had grown on a painted glass panel. The barnacle has penetrated the paint so completely that the details of the

of the metal is exposed to corrosion. The injury of coatings may be prevented if an antifouling paint is used. Such paints do not last indefinitely, however, and it is often desirable to protect surfaces which can not easily be repainted or to which the fouling is otherwise not a disadvantage. A hard coating will prevent penetration by barnacles. A sufficient amount of metallic or hard mineral filler in a bituminous coating may be an effective means of discouraging other types of boring or digging animals as well. Where the attack of the marine organisms is sufficiently slow, the most economical solution of the difficulty may be the use of cathodic protection against the localized corrosion (*8*).

On the credit side, a heavy growth of fouling may protect wooden structures from attack by wood borers. Figure 22 shows two wooden test blocks which had been exposed to the sea for one year at Miami. The one at the left is heavily fouled; that to its right has been cleaned periodically to prevent accumulation of the growth. When split open the fouled block was found to be almost free of wood borers; the cleaned block was much more seriously damaged (37).

Laboratory tests indicate that paints are attacked by bacteria in sea water. Some paints are decomposed more rapidly than others. Bacteria have been shown to attack many of the important constituents of the paint matrix such as rosin, paraffin, alkyd and phenolic resins, and linseed oil (24, 26, 30). Chlorinated rubber is decomposed slowly, while Vinyl resin, Halowax, coal tar pitch, and chlorinated styrene resist decomposition almost entirely. No data exist, however, as to how important the action of bacteria may be, as compared to the physical solution of the paint film by sea water under conditions of service.

GENERAL CONCLUSIONS

The preceding review of the ways in which fouling interferes with the proper functioning of structures and devices amply demonstrates the importance of the subject and the need for effective preventive procedures.

The principal harmful effect arises from the increased resistance which a structure roughened or enlarged by fouling offers to the movement through the water, or, conversely, to the movement of water past the structure. This is the case for the resistance of ships, treated in more detail in the following chapter, and in part for the flow of sea water in pipes and conduits. In other cases the harm is done by what may be described as a bulk effect, in which the fouling affects the weight or buoyancy of installations, plugs up orifices which should remain open, or interferes mechanically with moving devices. Special problems arise from the effects on sound transmission, the destructive action on paints, and the influence on corrosion.

Whatever the harm done by fouling, the essential remedy is to prevent the growth of the organisms, unless the simple procedure of removing them mechanically is practical. At present this can be accomplished most effectively by the application of toxic paints or greases, or by the use of metals which give off toxic ions as they corrode. In special cases toxics may be applied in solution directly

to the sea water, as in the case of powerhouse conduits. Success with toxics should not blind one to the possibility of finding other, more effective devices. Improvements in paint coatings are needed to ensure longer effective life, and particularly to develop systems less likely to be destroyed by the corrosion of the underlying steel. Coatings which may be applied successfully under the unfavorable conditions of weather frequently encountered in docking are greatly needed, as are special coatings adapted to various uses other than shipbottom application. Up to the present almost no effort has been expended in developing special alloys particularly adapted to resist fouling; such metals as are available are merely selected from among alloys devised for other purposes. Even the elementary facts regarding galvanic action in relation to its effects on both corrosion and fouling are frequently poorly understood by those responsible for the construction and maintenance of ships and other marine structures.

While interest in the biological aspects of fouling may appear to end with the discovery of toxic coatings capable of preventing the growth, it should be remembered that new protective devices can not very well be developed without a fundamental understanding of the fouling populations. New paint formulations can not be tested intelligently without this information. Finally, knowledge of the times and places where fouling is to be expected is necessary whenever there is any question of whether protective measures need be taken, how to practice such measures with the greatest economy, or how long structures will remain unfouled when protective measures can not be applied.

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