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## ENERGY (FUEL) CONSERVATION THROUGH UNDERWATER REMOVAL AND CONTROL OF FOULING ON HULLS OF NAVY SHIPS

by
H. S. Preiser, C. P. Cologer, and H. E. Achilles

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MATERIALS DEPARTMENT

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RESEARCH AND DEVELOPMENT REPORT

December 1975

Report 4543

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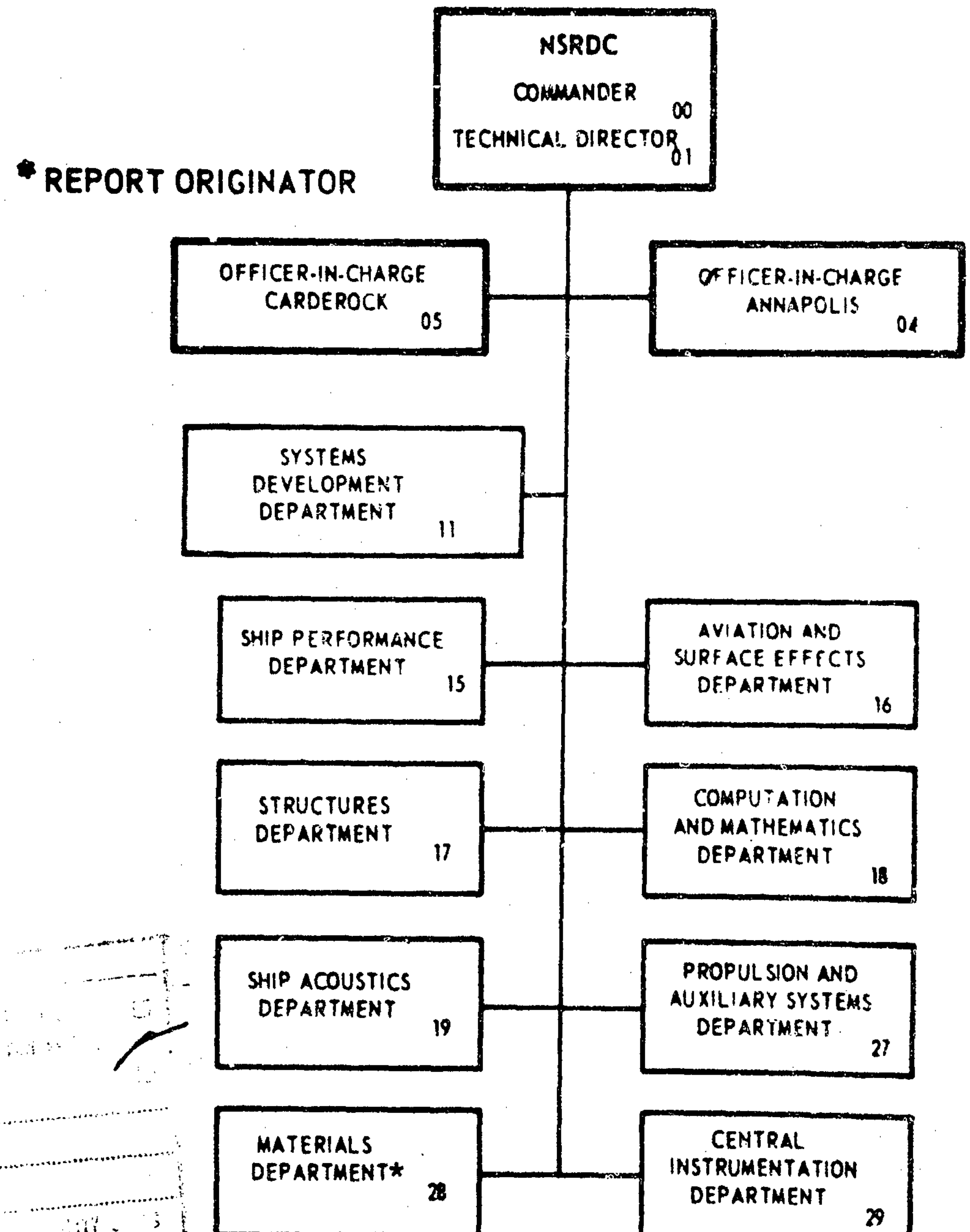


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Operating costs and performance efficiency of Navy ships have become matters of increasing concern because of the fourfold increase in cost and the unpredictable availability of foreign and domestic supplies of petroleum fuel. Methods whereby the Navy can conserve fuel are urgently needed. A systematic program for underwater removal and control of fouling is one method which → next page

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Abstract (Cont)

has considerable potential merit for attaining the objective of conserving fuel and improving ship performance. This report reviews the characteristics of fouling and describes underwater hull inspection and cleaning methods. It delineates the interactions among fuel consumption, fouling, and the compatibility of underwater cleaning methods with the antifouling paint coating on the hull. It also presents an integrated concept of hull cleaning and fouling control. A program plan is described which, when completed, is presented to result in the conservation of fuel and improved ship performance through the development and Fleet-wide implementation of cost-effective underwater hull-cleaning methodology to remove and control fouling on Navy ships. Conservative estimates place this fuel saving at 15% of the total quantity consumed by the Fleet. With respect to effective control of fouling, this should assure attainment of the current Navy objective of making ships available for 5 years between successive drydockings.

(Authors)

## ADMINISTRATIVE INFORMATION

This project is part of the United States Navy's Energy Conservation Program. The project is sponsored by the Naval Sea Systems Command (SEA 0331G), Mr. C. L. Miller, and is funded through Program Element 64710N, Task Area S41W2, Task 18313, Work Unit 2841-116. Project direction is given in reference (a) which constitutes the authority for the project.

The work has been accomplished in the Elastomers and Coatings Branch of the Nonmetallics Division of the Materials Department of the David W. Taylor Naval Ship R and D Center. The program officers are LCDR B. P. Sack and LT. L. A. Lukens. The program coordinator is Dr. D. R. Ventriglio. The principal investigator is Mr. H. S. Preiser. Contributors to this report were Mr. G. S. Bohlander for development of data concerning commercial hull cleaning methods, Mr. D. R. Laster and H. F. Koch for development of background information concerning ships' performance, and the Center's diving team Messrs. F. A. Sampson, M. F. Oakes, A. P. Partlow, Sr., and E. L. Whitmore for the underwater photography, inspection, and cleaning.

This progress report describes the results of work performed from 1 November 1974 through 31 March 1975.

## ADMINISTRATIVE REFERENCE

(a) NAVSEA Energy R&D Program, NAVSEA ltr SEA 033/JRG of 25 Oct 1974

## LIST OF ABBREVIATIONS

| | |
|---|---|
| rpm | - revolutions per minute |
| AF/AC | - antifouling/anticorrosion |
| psi | - pounds per square inch |
| gpm | - gallons per minute |
| $\mu g/cm^2$ | - microgram per centimeter square |
| $A/ft^2$ | - ampere per square foot |
| et al | - and others |
| $\mu g/cm^2/d$ | - microgram per centimeter square per day |
| hp | - horsepower |
| a-c | - alternating-current |
| std | - standard |

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## INTRODUCTION

The operating costs and performance efficiency of Navy ships have become of increasing concern recently because of the four-fold increase in cost and the unpredictable future availability of foreign and domestic supplies of petroleum fuel. Most Navy surface ships are expected to continue to be powered with petroleum fuel, although a relatively small number will be nuclear powered.[1]

The number of Navy ships available for missions has decreased substantially within the last several years. Those ships that are available must operate efficiently and economically for sustained periods to assure overall mission accomplishment with minimal fuel consumption.

Naval experience has shown that because of fouling, fuel consumption is increased significantly with a corresponding increase in fuel cost. Improved underwater maintenance of the hull and appendages is an area of ship support which has a well-founded expectation of providing significant savings in fuel and maintenance labor costs. Assuming that maintaining hulls and propellers relatively free of fouling marine growths would have resulted in a 15% overall decrease in fuel consumption, the destroyer Fleet in 1973 would have had a gross fuel savings of approximately $20,000,000 per year (fuel at $15 per barrel basis) with operational schedules remaining constant.

Progress in hull paint technology and increased knowledge of the behavior and life cycles of fouling organisms has led to improved antifouling paints, with service capabilities as long as 3 years, depending on environmental and operating factors. However, severe fouling has occurred in some cases, especially for ships operating in tropical waters. This Center, under sponsorship of the Naval Sea Systems Command, is developing an improved long-life antifouling paint containing organometallic polymer toxics which will be environmentally acceptable and are effective in preventing attachment of a wide range of fouling organisms for extended periods. However, this approach is a long-term effort and cannot address immediate needs for fuel conservation.

[1] Superscripts refer to similarly numbered entries in the Technical References at the end of the text.

Another approach to reducing the adverse effects of fouling is periodic underwater hull cleaning which already has found commercial acceptance.[2] New techniques and cleaning tools have been designed which not only remove fouling growths but also are reportedly capable of rejuvenating antifouling paints,[3,4] thereby improving ships' performance and extending the intervals between drydockings.

The following subjects are discussed in this report:

- The nature of fouling.
- The interaction between fuel consumption and fouling.
- Underwater hull inspection methods.
- Underwater hull cleaning methods.
- Fouling prevention techniques.
- The integrated concept of cleaning/fouling control

A program plan to conserve fuel and improve ship performance through the development, evaluation, and Fleet-wide implementation of cost-effective underwater hull cleaning methodology to remove and control marine fouling growths on Navy ships is presented. With respect to the control of fouling on ship hulls and appendages, it is an objective of this program to assure ship availability for 5 years between successive drydockings.

## THE NATURE OF MARINE FOULING[5]

Some basic knowledge of the organisms that make up fouling is helpful in understanding how fouling may be controlled. Individual fouling organisms attached to the hull of a ship vary in size, shape, complexity, and behavior. For example, sizes can range from microns for unicellular diatoms to several inches for tubeworms. Formation of a fouling community at a specific location on a ship is a function of time and other factors. It is also dependent on the resistance of fouling organisms to the toxicity of the antifouling paint. Different organisms proliferate at different rates. For example, a colony of bacteria forms a slime within a few hours;[6] whereas the development of a barnacle from the cyprid stage to the young, attached cyrral feeding barnacle may require several days.[7,8] Most common types of marine fouling organisms may be identified as follows.



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SLIME

Slime is a mucoidal layer of unicellular microscopic organisms including many varieties of algae, bacteria, diatoms, and protozoa[9] strains of which are resistant to many toxic materials. This form of fouling in the incipient stage is difficult to detect underwater by visual means but is discernible by direct touch and is considered to play a significant role in increasing frictional drag, especially on propellers.[10,11] Slimes also form an obstructing layer over the antifouling paint which prevents or retards the release of toxic components to the water interface and thereby encourages the growth of more severe forms of fouling. There is also considerable evidence that slime bacteria degrade the organic paint resin, accelerating paint film failure.[12] A typical slime growth is shown in figure 1.

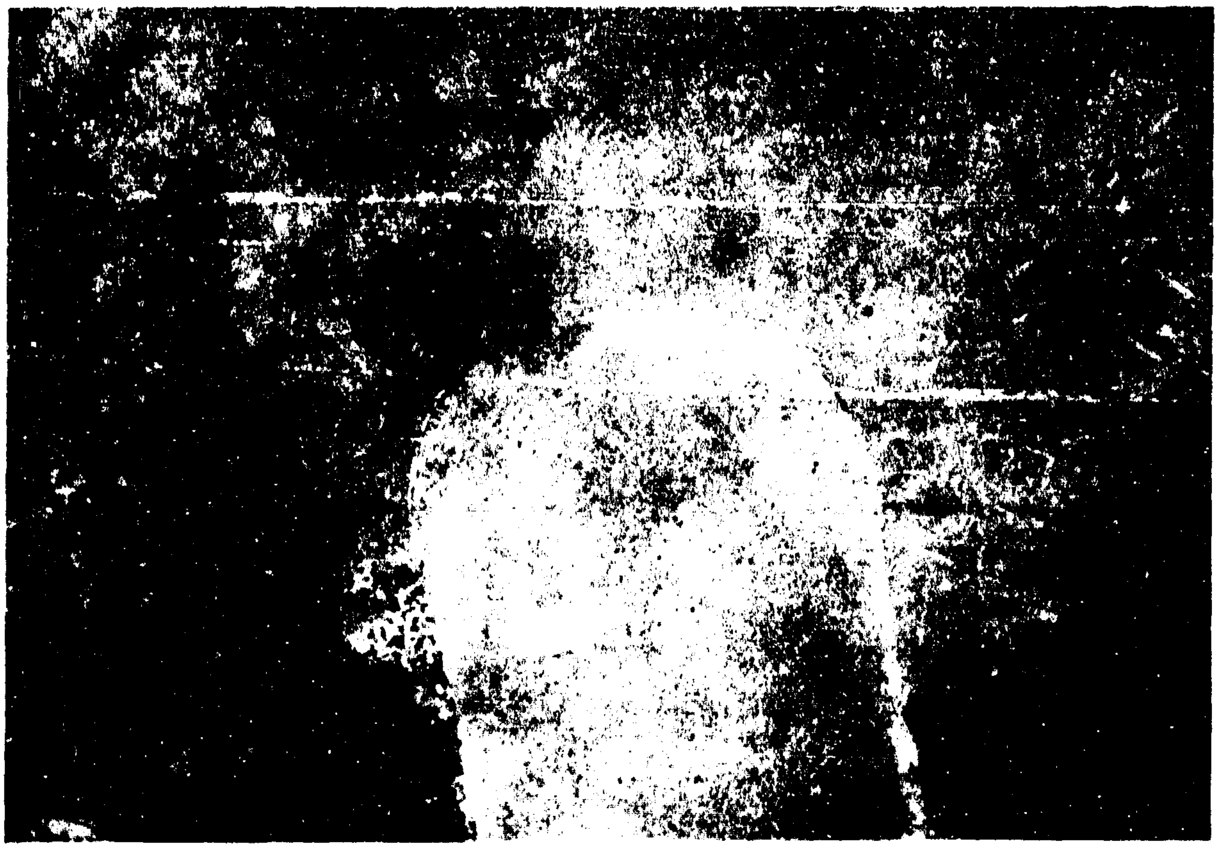


Figure 1
Typical Slime Growth
Compared to Central Portion
Cleaned with a Rotary Brush

OTHER NONCALCAREOUS FORMS

Noncalcareous fouling consists of multicellular organisms comprising principally algae, hydroids, tunicates, and some bryozoa[6] and usually is the first visible evidence of fouling. In the incipient stage it is termed, "grass". Some forms of grass are resistant to the more common copper base antifouling paints. However, fouling by certain grasses may be controlled more effectively by tin base antifoulants. A typical grass growth appears in figure 2. Removal of grasses by means of underwater brushing can be accomplished without damaging intact paint films or roughening of the hull.[2,13] Grasses increase hull friction to an even greater extent than slimes.[14]

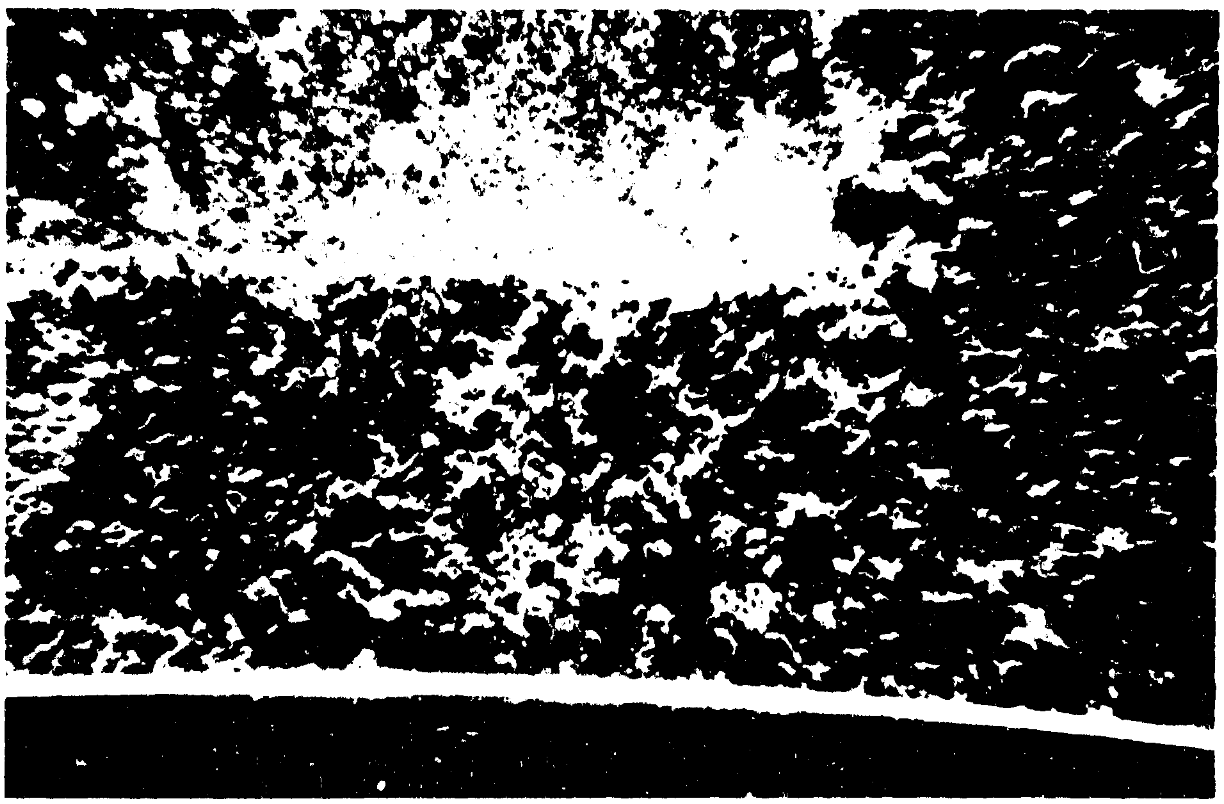


Figure 2
Typical Grass Growth
Compared to Cleaned Portion of Hull

CALCAREOUS FORMS

Calcareous forms, shown in figure 3, include barnacles, tubeworms, encrusting bryozoa, and oysters[15,16] and usually are present with the noncalcareous organisms described previously. The presence of calcareous organisms indicates diminishing effectiveness of the antifouling paint.[17] As the growth of calcareous forms becomes more severe, frictional drag often reaches intolerable levels as indicated by major increases in fuel consumption required to maintain operating speeds. Removal of this type of fouling is more difficult and time consuming and, in general, damages some of the underlying paint system, as reported by industry and observed by divers of this Center. In less severe cases of fouling, removal of the growth may damage only the antifouling coating. However, removal of the more advanced stages of fouling growth may damage both antifouling and anticorrosive coatings. Underwater removable of such fouling has been accomplished by brushes with bristles made of steel, plastic-coated steel, or plastic, and by means of hydraulic jets.

Figure 3
Calcareous Fouling on Hull

CLIMAX FOULING COMMUNITY

Certain types of organisms may modify an immediate environment or by other means may establish conditions favorable for a succeeding community of organisms referred to as "climax" fouling communities. At a specific stationary location such as pilings, the climax community, is the final stage of biotic succession which is so stable that no further change may be anticipated. On the hull of a ship which is mobile, the final stage of succession may be considered to be in a quasi-dynamic equilibrium. In addition to the sedentary organisms, living on the submerged surface, the climax community includes foragers and predators such as crawling and clinging organisms feeding on others which make up the community. This advanced and readily visible stage is observed more commonly on buoys and piles than on the hulls of ships. Ships with hulls in this advanced stage of fouling should be, preferably, drydocked, cleaned, and repainted.

## INTERACTION BETWEEN FUEL CONSUMPTION AND FOULING

HULL FOULING

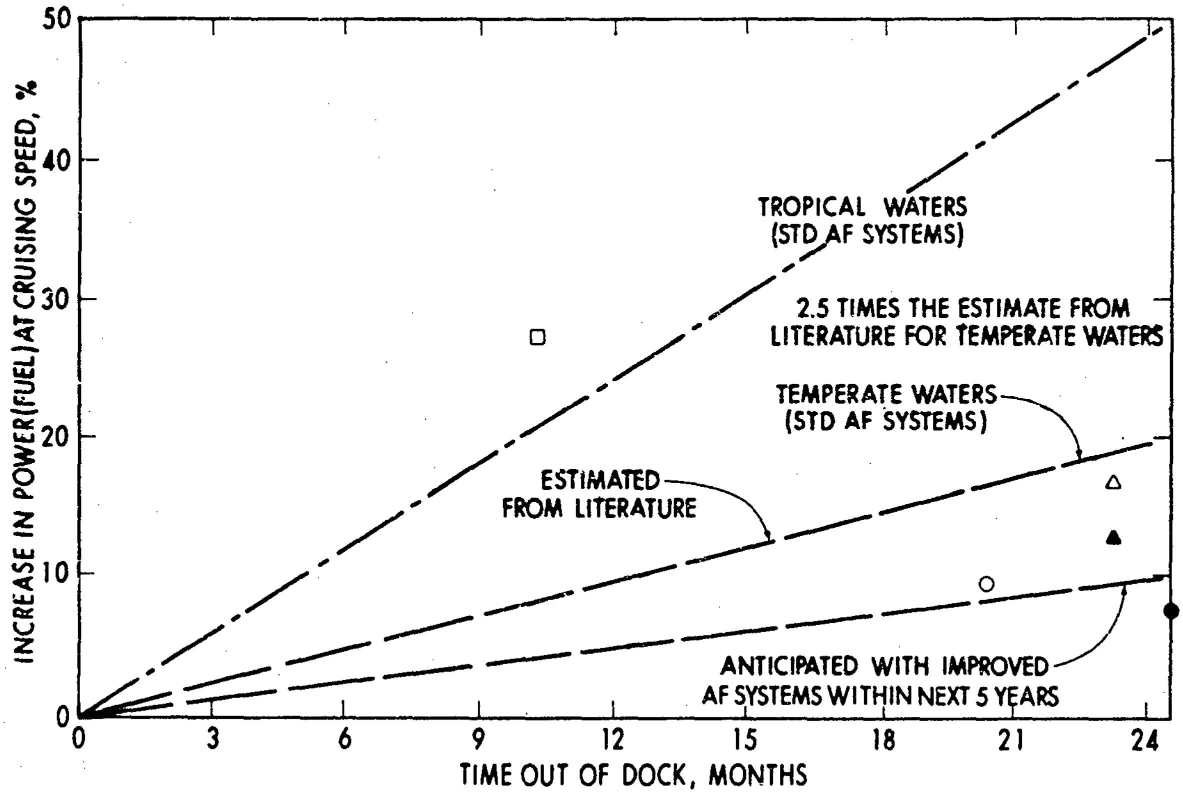
The effect of fouling on ship performance and related fuel consumption has been a subject of major interest to naval architects and hydrodynamicists for many years. Much progress had been made toward predicting full-scale ship performance from that of models since the time of Froude and Reynolds.[18,19] However, because of out-of-scale roughness factors associated with real ship hulls as compared to smooth models, it still is necessary to perform full-scale standardization trials to correlate measured performance with predicted performance.[20]

In a comprehensive paper presented at the 17th American Towing Tank Conference (ATTC) 1974, McCarthy[10] treated the effects of fouling on increased frictional drag of ships within the framework of current knowledge. The author stated that "Distributed surface roughness is a major drag source on all new ships. When in service, fouling of hulls and propellers is rapid, resulting in serious degradation of the performance and economy of every ship, no matter how well it is designed hydrodynamically."

A study of the literature has disclosed a paucity of data on actual measurements of increases in ship power required to maintain a given speed as a result of fouling. Since the severity of fouling is dependent on a wide range of environmental factors, ship operation factors, and hull paint systems, no hard and fast rule can be drawn as to the exact effects of fouling on ship performance. However, on the basis of scattered information from primary literature sources,[10,20,21,22,23,24,26] a composite curve was constructed (as shown in figure 4) which estimates conservatively the power increases that may be expected from the fouling of naval ships as a function of time out of dry dock. The hydrodynamic aspects of ship performance as affected by fouling are discussed more fully in appendix A.

Actual Trial Data Points:

| Symbol | Ship | AF Paint | Speed* |
|---|---|---|---|
| ○ | Frigate | Vinyl | 80% Full rpm* |
| ● | Frigate | Hot Plastic** | 80% Full rpm |
| △ | Destroyer | Vinyl | 59% Full Power |
| ▲ | Destroyer | Hot Plastic** | 59% Full Power |
| □ | Submarine | Vinyl | 80% Full Power |




*See R. J. Stenson.[23]
**Initial hull roughness higher than for vinyl.

Figure 4
Estimated Power Increase Required for Naval Ships Due to Fouling Versus Time Out of Dock

*Definition of abbreviations used may be found on page i.

Several assumptions and extrapolations have been made in the plotting of figure 4.

- Fouling roughness rates are linearized for simplified mathematical treatment, although trials data provide a basis for curves whose slopes increase positively with time.[20,21,22]

- The frictional resistance of the ship at cruise speeds is equal to 50% of its total resistance.[10]

- Anticipated near term improvements in antifouling/anticorrosive paint systems would decrease fouling accumulation and its consequent roughness by 50%.[3,4]

- Fouling rates and consequent roughness in tropical zones are at least 2.5 times more severe than in temperate zones, exclusive of propeller fouling,[23] on the basis of British experience.

Actual trials data, shown in figure 4, support the estimated trends for increased power versus time out of dock.

Data developed by others and summarized by Jourdain and Muntjeiverf[25] show that between 10% and 23% more power is required to attain a given speed because of fouling on both hull and propeller on merchant ships over a 1-year period out of drydock. For design purposes, the British Admiralty allows an increase in frictional resistance of a ship of ¼% per day out of dock in temperate waters and ½% per day in tropical waters.[22] The above design allowances for increased frictional resistance and the concommittant power increase required to overcome this resistance are founded on earlier British paint practices. Such power increase is much greater than that which actually has been experienced with ships of the United States Navy. This information tends to support the conservative estimates made for power increases due to fouling on ships with Navy paint systems, as plotted in figure 4.

PROPELLERS

Fouling accumulations have been observed on propellers of Navy and merchant ships remaining in port for extended periods.[23,25] Divers of this Center routinely have removed fouling from propellers of ships while accomplishing scheduled underwater cleaning operations on fouled sonar domes. In fact, Navy practice requires that divers using hand tools remove fouling from propellers of certain ships prior to departure. Although no systematic full-scale data have been accumulated concerning the effect of propeller fouling on fuel consumption, strong evidence in the literature indicates that surface roughening has a marked effect on decreasing propeller efficiency (propulsive coefficient),[26,27,28,29] as illustrated in figure 5. In one comprehensive study by Kan, et al,[30] full-scale and model propellers were artifically roughened with protuberances simulating various levels of severity and extent of fouling. It was concluded,"... roughness all over the blade surface generally produces a worse effect on the propulsive efficiency of the ship than that produced by corresponding fouling of the hull surface". Kan also presented tugboat trial data which showed an increase of 10% to 30% in shaft horsepower at a fixed speed as a result of propeller fouling alone after 40 days exposure.[30] Ferguson[28] also documents that fouling of a bronze propeller can reduce propulsive efficiency drastically. It is apparent that propeller fouling has a major effect on increased fuel consumption.[10]

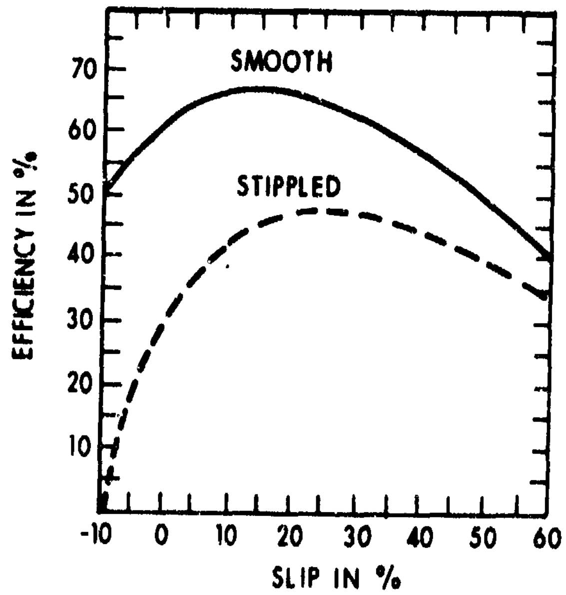



Figure 5[27]
Comparison of the Efficiency of a Model Propeller in the Smooth Condition and After Roughening by Stippling a Wet Coating

SEA CHESTS

The fouling and clogging of sea chests is another serious shipboard problem that merits attention. Such fouling is not significantly related to hull drag but interferes with efficient power plant operations by reducing cooling water flow, hence increasing fuel consumption.

ESTIMATED FUEL COST OF FOULING TO THE NAVY

Petroleum fuel consumption by all Navy ships amounted to 45,900,000 barrels in 1973 according to Lukens, et al.[31] The authors also determined that warships consumed 50.8% of the total Navy ships' energy usage. Excluding nuclear power, energy or petroleum consumption of the 195 destroyers amounted to 59.2% of the total Navy ships' fuel usage, or approximately 13,800,000 barrels. A sample of Fleet petroleum fuel consumption records for 15 typical destroyers indicated that 64% of total fuel consumption in 1973 was required for propulsion purposes. By applying this propulsion fuel ratio to total Navy destroyer fuel consumption in fiscal year 1973, it can be calculated that 8,830, 000 barrels would be consumed for propulsion purposes. Assuming that 15% of propulsion fuel consumption is attributable to fouling (see figure 4) the fuel cost of fouling is approximately 1,320,000 barrels or, at $15 per barrel, an annual gross fuel cost of about $20,000,000 for the 195 destroyers ($102,000 per year per destroyer).

If the above assumed 15% of propulsion fuel attributable to fouling is applied to the sample of 15 destroyers for which returned fuel consumption records were obtained, a fuel cost of some $91,500 per year per destroyer is estimated. This sum is somewhat smaller than the $102,000 mentioned previously and reflects the less than average total fuel consumption of these 15 ships.

## UNDERWATER HULL CLEANING METHODS

The chief measure to date for countering fouling has been the use of toxic antifouling paints. Although these paints retard the fouling process, especially of the calcareous forms, they are not completely effective, as evidenced by the data on fouling rates presented for ships protected by antifouling paints. As a result, ships are periodically drydocked for removal of fouling and renewal of the antifouling coating, a very expensive operation. In recent years, some new approaches to fouling control have been developed which involve underwater cleaning of ship hulls.[32,33] These methods offer several advantages over conventional cleaning in drydock:

- Removal of fouling can be accomplished with minimum interruption of or interference with other shipboard activities.

- Steps to remove fouling are relatively simple.

- Handling and control of hull cleaning equipment are enhanced by buoyancy forces associated with underwater operations.

- Periodic underwater removal of light fouling from ship hulls, as compared to infrequent removal of heavy fouling in drydock, lessens the atmospheric pollution and reduces the concentration of dead organisms returned to the harbor per cleaning operation.

Some of the disadvantages of underwater hull cleaning that merit consideration are:

- Excessive paint wear or damage can occur with improper control of cleaning tools by the diver.

- Limited visibility underwater sometimes interferes with efficient cleaning operations and inspection.

- Safety requirements are stringent for personnel involved in underwater hull-cleaning operations.

BRUSH CLEANING

At present the majority of underwater cleaning operations are performed with various types of rotary brushes. Bristles of the brushes may be of different shapes, sizes, and compositions such as steel, plastic coated steel, or plastic. The complexity of brush systems varies widely. The simplest involves the use of a diver-controlled rotary brush,[33] as shown in figures 6 and 7. A self-propelled remote controlled vehicle identified commercially as SCAMP, a registered trademark of Butterworth Systems, Incorporated, employs multiple circular rotary brushes.[3] Views of a SCAMP unit and its remote control unit are shown in figures 8 and 9, respectively. Another approach is a "Brush boat"[34] which is equipped with cylindrical rotating brushes and can be maneuvered around the hull of a ship which is being cleaned. Figure 10 shows a Brush boat in operation.

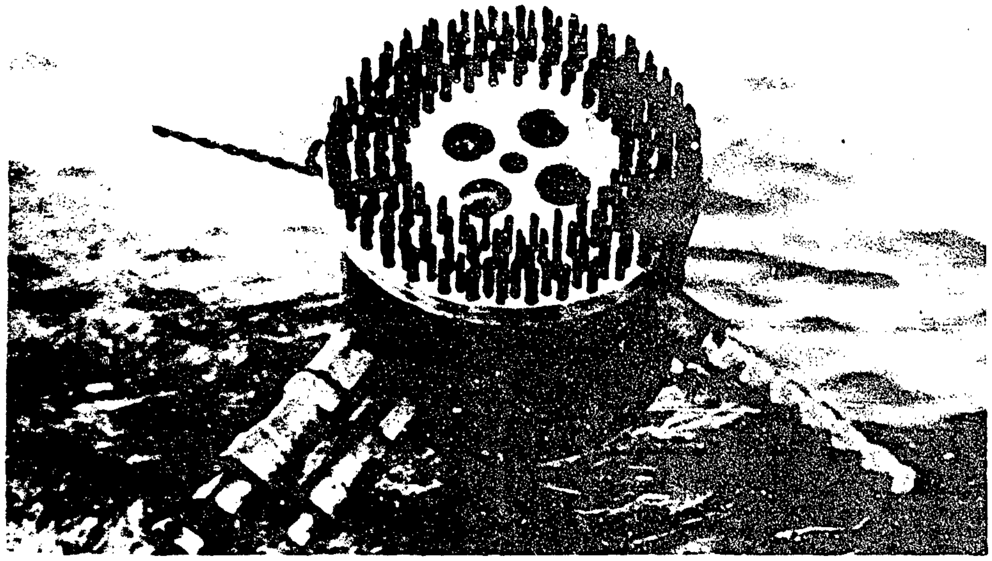


Figure 6
Diver Controlled Rotary Brush Assembly

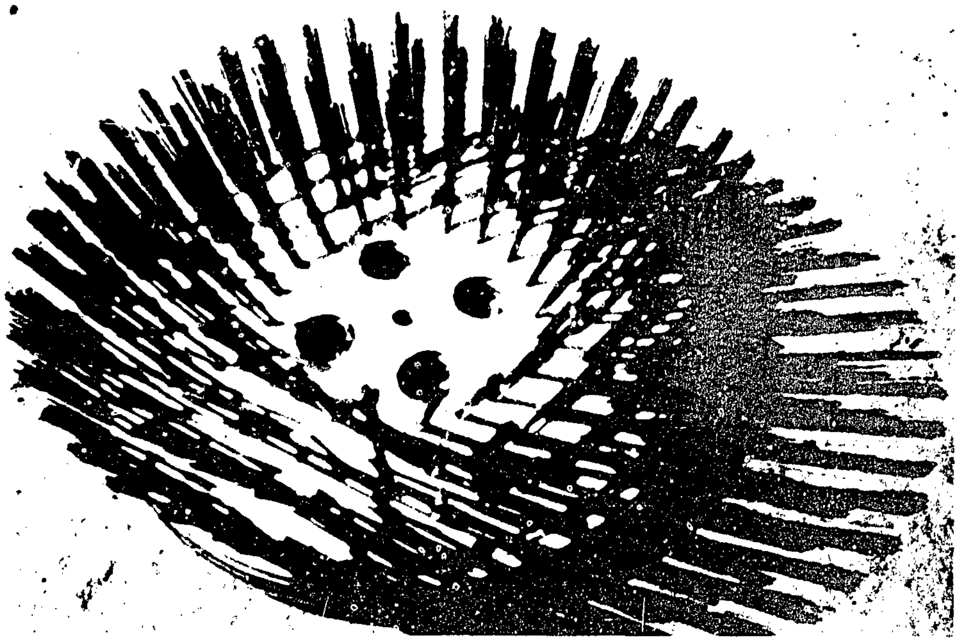


Figure 7
Typical Cleaning Brush

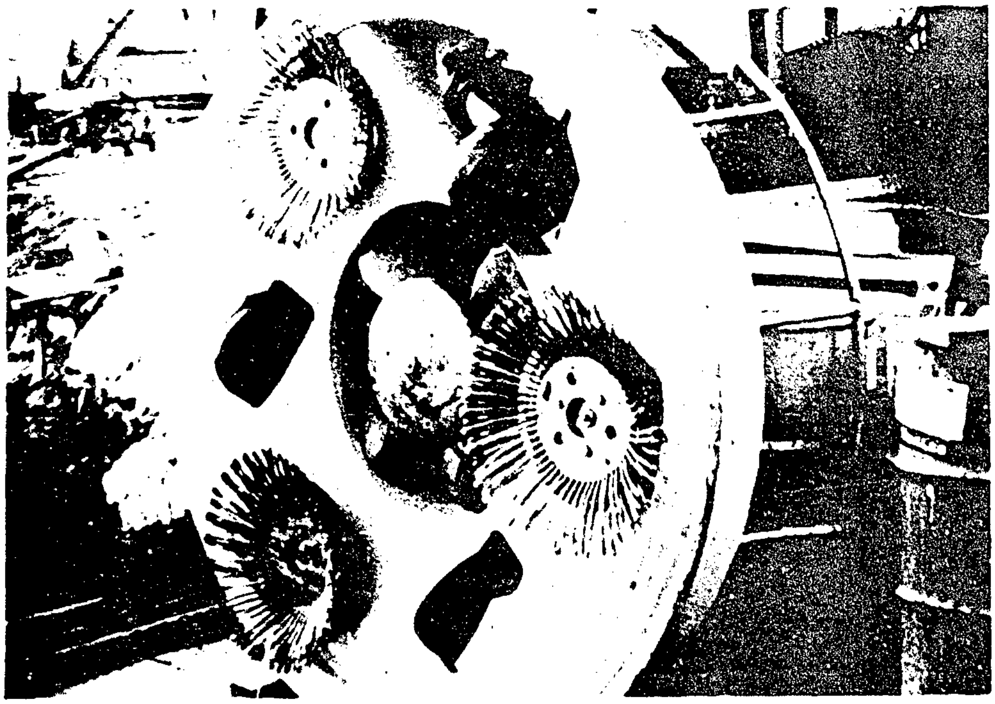


Figure 8
Underside of "SCAMP" Cleaning Unit

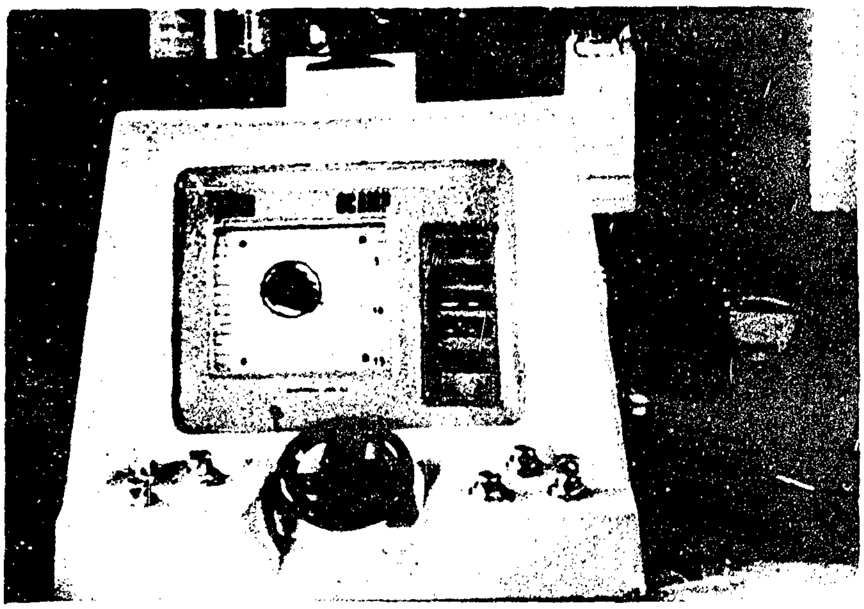


Figure 9
"SCAMP" Control Console

Figure 10
Brush Boat in Operation, Rotating Brush
Extends Vertically Below Surface
Approximately 8-12 Feet

Common features of rotary brushes include:

- They create a differential pressure (similar to a pump impeller) which holds the brushes in close contact with the hull.

- When properly designed, the brush bristles wipe rather than abrade the growth from the hull and then discharge the debris away from the brush. In these cases the AF/AC paint is left relatively undisturbed. Also, the bristles may be so designed that they gently abrade the AF coating and rejuvenate it.

- The travel of the brush along the hull surface is controlled by the direction of the rotation and the location of peripheral contact with the hull surface.

The severity and rate of cleaning can be controlled by the contact pressure, rotational speed of the brush, physical design, material characteristics of the bristles, the number of bristles per brush, and the diameter and number of brushes in the rig. Large multibrush systems are claimed to be effective in cleaning flat surfaces such as the sides and bottoms of hulls but are unsatisfactory for cleaning surfaces or appendages with small radii of curvature. Appendages, struts, bosses, and propellers must be cleaned by divers operating single units.

On the basis of information already available from commercial sources,[2,11,13,34] and observation of the cleaning of the hull of a destroyer,[35] the brush system, at present, appears to be a very effective means to remove fouling of both the noncalcareous and calcareous types described previously.

HYDRAULIC JET CLEANING

Various types of jets have been considered for underwater hull cleaning. The simplest jet delivers a stream of water at pressures up to 10,000 psi at 20 gpm. A jet of this type[36] is used in many industries to remove rust and scale and to clean heat exchangers, reaction vessels, etc. It also has been used successfully to clean debris and loose paint from hulls in drydock, but effective operation of the unit underwater has not been fully demonstrated. Sand, aluminum or other blast media can be introduced in the straight hydraulic jet[37] which enhances the potency and rate of cleaning. Another slurry type jet rig uses compressed air to dewater a space underwater contiguous to the surface that is being cleaned.[38]

The technology of underwater jet cleaning is in an early stage of development, and some existing problems are still to be resolved. Diver controlled jet systems require compensating bleed-off capability to impart stability and to permit easy handling. Redesign of the jet tool is required to permit broad and rapid coverage of the area to be cleaned. Means to maintain the jet nozzle at the proper distance from the fouled surface and to assure controlled translational motion of the jet over the surface would have to be incorporated in the overall design of a practical unit. A view of a proposed design of jet gun for underwater cleaning is shown in figure 11. With its various potential modifications, the jet seems to have sufficient merit to warrant a limited laboratory investigation of its effectiveness for underwater hull cleaning.

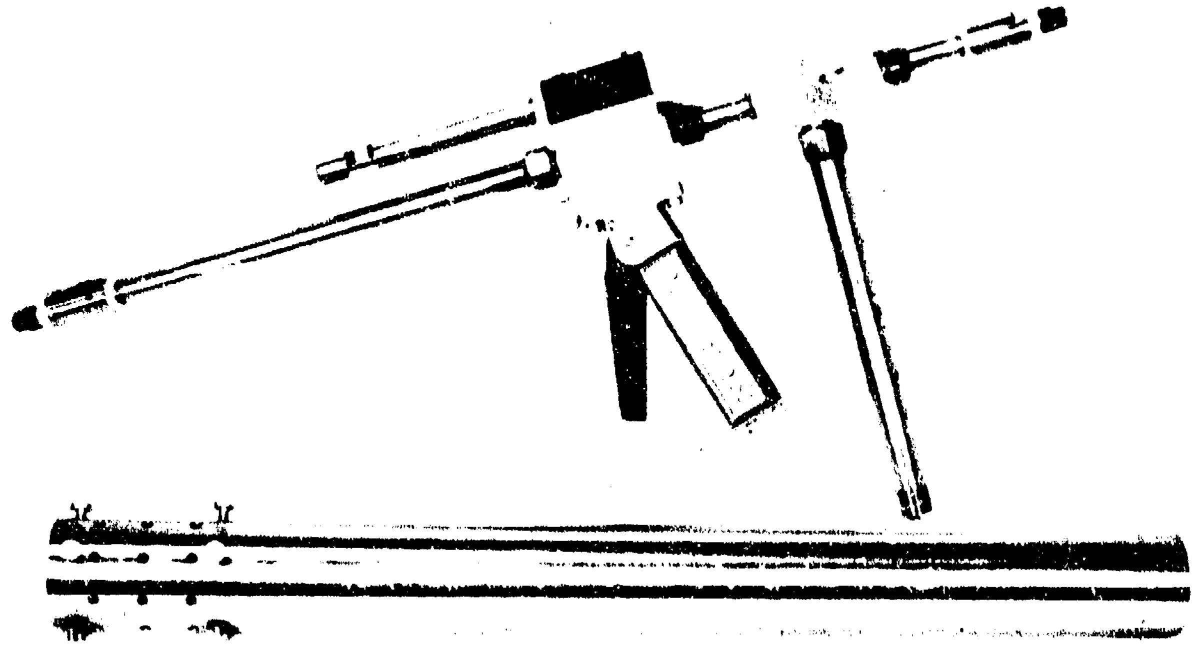


Figure 11
Proposed Underwater Type Jet with Backthrust
Diffuser Shown Below

CAVITATIONAL JET CLEANING

Several companies are investigating the use of jets in which cavities are introduced and carried downstream to implode on the surface to be cleaned. Utilizing the forces of cavitation[39] in this manner develops high impact forces at considerably lower hydraulic pressures than for conventional jets, thereby increasing the potency of the jet action. At present the National Maritime Research Center, Galveston, Texas, is sponsoring a feasibility study of a process identified by the trademark, "Cavijet", under development by Hydronautics, Incorporated.[40]

So far, preliminary experiments have shown the Cavijet to be capable of cleaning severely fouled surfaces to a bare metal substrate. Thus, the cavitation jet may be useful for removal of advanced stages of fouling from a ship prior to drydocking as a labor-saving technique in preparing the hull for represervation.

Cavitational jets are capable of producing impacts sufficiently powerful to drill into or cut metals. Because of the relatively low hydraulic pressures involved, reaction compensation is easily accomplished without undue loss of efficiency, according to the developer. Cavitational jets appear to have advantages when cleaning highly contoured, recessed, or relatively inaccessible areas such as sea chests not readily reached with brushes or other cleaning tools, but careful control of their force appears necessary when paint is not to be removed.

## EXPLOSIVE REMOVAL OF FOULING

Systematic controlled explosions detonated close to hull surfaces constitute a novel means of removing fouling. The "Sea Mesh System," a trademark of Controlled Dynamics Corporation,[41] employs a net fabricated of cords containing explosive cores. The net is suspended or floated a short distance from the hull. When the explosive is detonated sequentially, the ensuing underwater shock wave radiating outward from the cores travels along the length of the hull and literally blasts fouling growths off the hull.

Although the method would appear to have some merit, it does have several serious disadvantages which must be remedied before the system may be considered practicable. Several demonstrations on Navy and commercial ships[42,43,44] have disclosed that some residual fouling remains which requires removal by auxiliary methods. In one application involving a merchant ship[45] engine gage glasses were popped from mountings, light bulbs were broken, and bathroom fixtures were cracked as a result of the underwater explosions. Consequently, when explosive systems are used, it is necessary to observe appropriate precautions in order to avoid damaging potentially vulnerable areas of ship hulls as well as interior fittings and equipment. The environmental impact on marine life of underwater explosions also requires careful utilization of this technique.

Further development of the system obviously is necessary before it can be considered viable. Future demonstrations arranged by others will be followed and evaluated, but laboratory evaluation of the technique is not considered warranted at present.

# INTEGRATED CONCEPTS OF FOULING CONTROL

## ANTIFOULING PAINTS/PERIODIC UNDERWATER CLEANING

The removal of fouling should not be considered simply as an isolated action but as part of an integrated concept, the principal components of which include means of fouling removal interacting with the AF/AC hull coatings. This concept is being demonstrated by a study at NAVSHIPYD PEARL,[3] where the current investigation includes periodic hand brush cleaning of test panels coated with a variety of antifouling formulations and exposure to a severe fouling marine environment. Two of these panels, represented by figures 12 and 13, have 20-mil thick coats of Navy formula 121/63 and have been under observation for a 24-month period. Figure 12 presents determinations made for fouling resistance and leaching rates at 3-month intervals on an unbrushed panel. Figure 13 presents similar data for a panel that has been brush cleaned every 3 months and includes determinations for fouling resistance and leaching rates before and after each brush cleaning. Selected observations of data in figures 12 and 13 show that:

- Fouling resistance of the unbrushed panel declined at a faster rate after the 9th month to complete loss of fouling resistance by the 24th month.

- The leaching rate of the unbrushed panel continued to decrease during the entire period of exposure.

- Fouling resistance of the brushed panel was maintained above 90% for the entire period of exposure.

- The leaching rate of the brushed panel increased markedly after each brushing.

- There was a marked change in leach rate after each brushing, even when there was no visible evidence of fouling.

Alteration of leach rates may be explained on the basis that slime films, invisible to the naked eye, form on the surface and in effect constitute a slightly permeable barrier which retards the rate of solution of the toxic substance in seawater. The removal of these slimes, especially on surfaces free of visible fouling, allows a significant increase in leaching immediately after brushing. Besides cleaning away slime, brushing also may affect leaching rate by removing the outer layers of paint deficient in toxic and exposing hitherto underlying paint with its available store of toxic. In addition, brushing may extend the service life of the antifouling paint by removing slimes and grasses which promote biodeterioration of the paint matrix and ultimate breakdown of the paint film.[12] It is the purpose of the present program to consider such parameters as hardness, resilience, surface texture, thickness, type, and degree of toxic loading in order to select the coating system most physically and chemically compatible with periodic mechanical cleaning of its surface. Coatings whose surfaces are not roughened during the cleaning process will be of special interest.

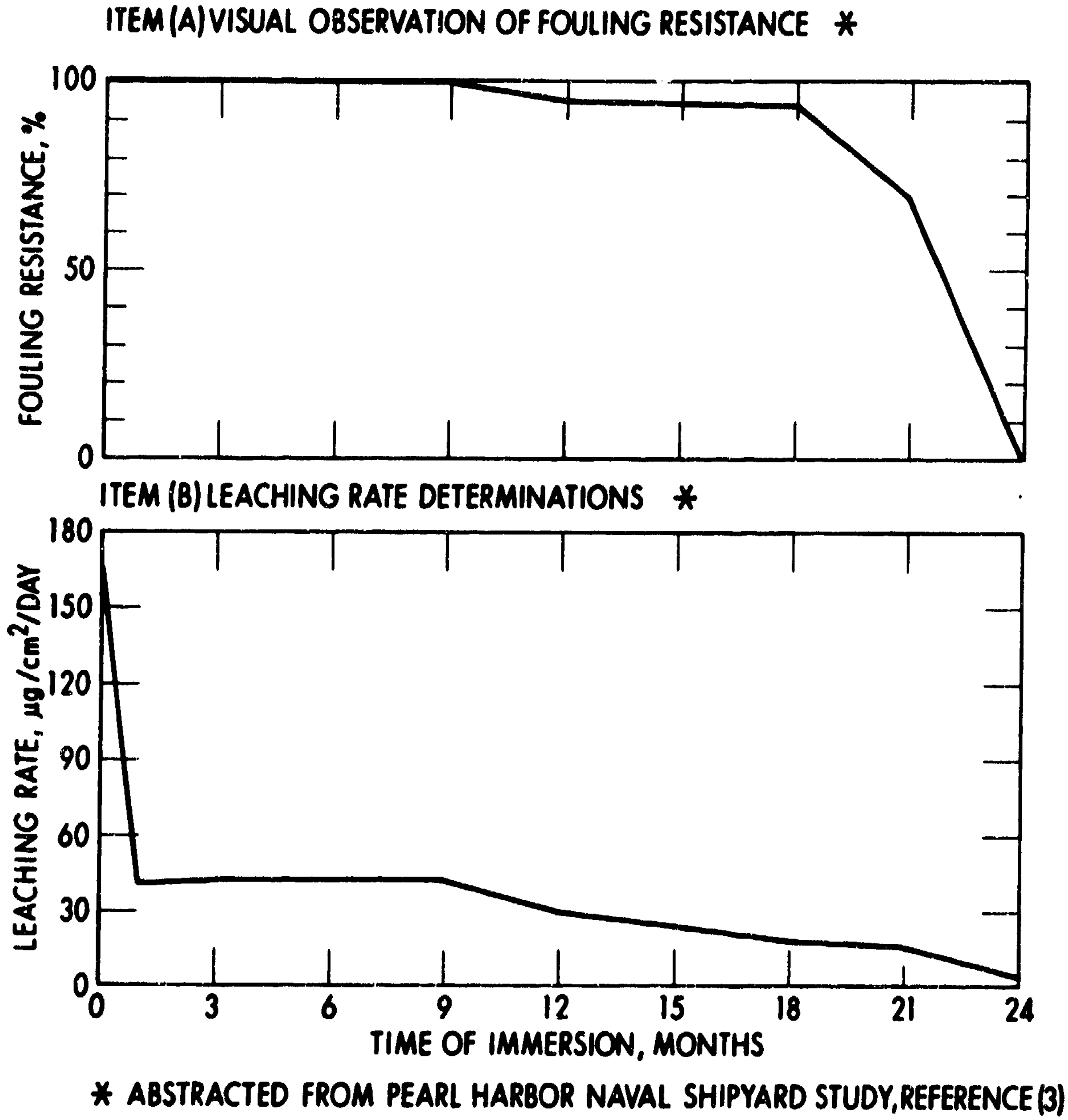



Figure 12
Antifouling Paint: Navy Formula 121/63 (Red);
20 Mils Thickness, Test Condition: Standard
(No Brushing); Toxin: $Cu_2O$; Analysis: Copper

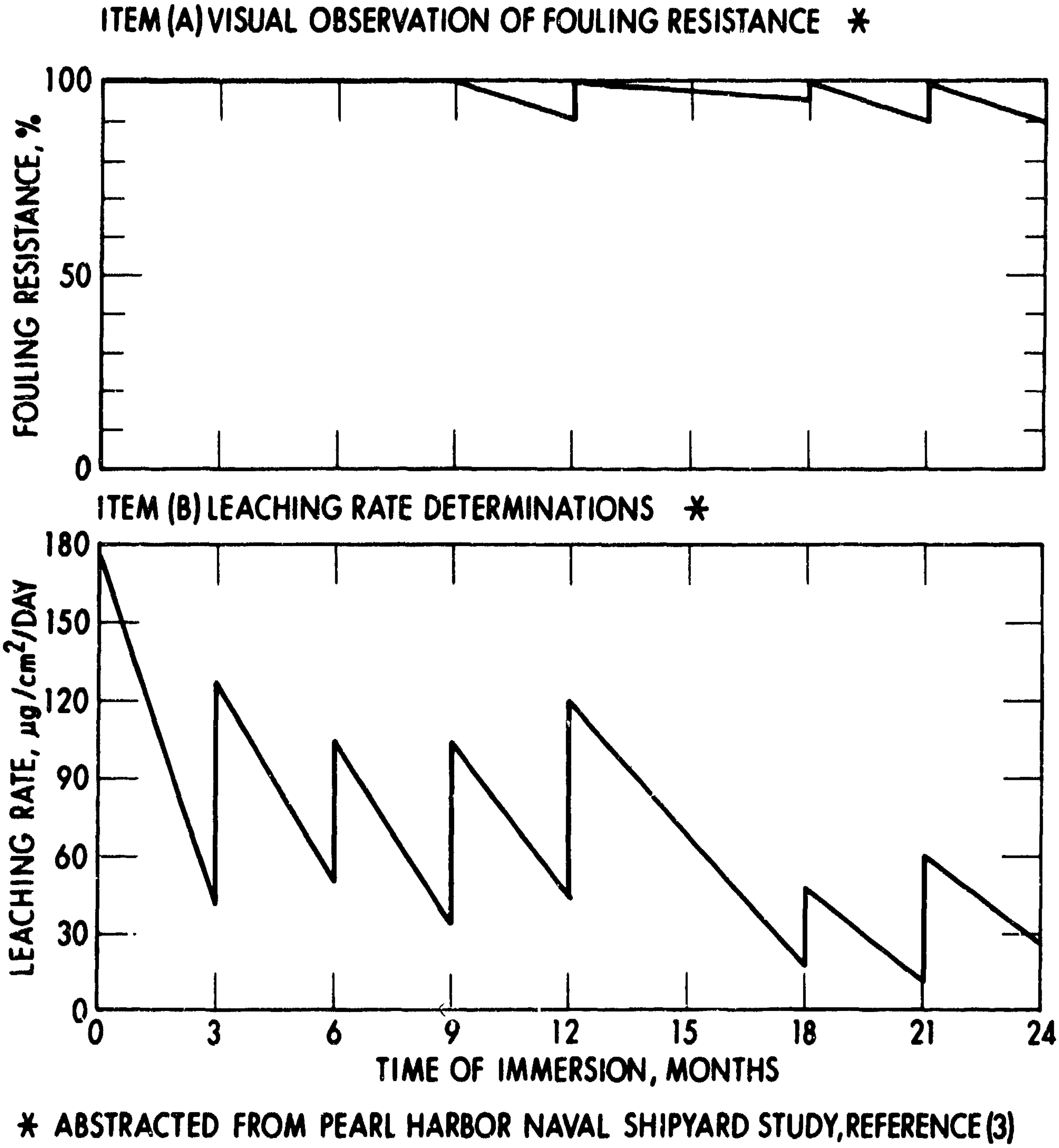



Figure 13
Antifouling Paint: Navy Formula 121/63 (Red); 20 Mils Thickness, Test Condition: Brush Every 3 Months; Toxin $Cu_2O$; Analysis: Copper

A hull protective paint system compatible with brush cleaning has become commercially available recently.[46] Periodic controlled cleaning reactivates the spent antifouling coating and is reported to extend the life of the system up to 5 years between renewals of the antifouling topcoat. The system utilizes a thick (10 mil), well applied, durable anticorrosive system over which is applied several layers of a brushable cuprous oxide antifouling paint. The spent paint is removed by underwater brushing at the rate of 1 to 2 mils per year. The brushes are designed to remove the spent soft outer layer of the antifouling paint without damaging the intact harder underlayer. A change of color from green to red during brushing alerts the diver when restoration of the surface is completed.

A review of the mechanisms by which antifouling coatings perform their function is given in appendix B. It is apparent that since these coating systems will have to interface with mechanical cleaning methods, an understanding of their structure and function is important for optimizing an integrated concept of fouling control.

NONTOXIC PAINTS/PERIODIC HULL CLEANING

Conceivably, hard, glassy coatings which fill in surface voids could be expected to decrease frictional drag substantially on the basis of preliminary studies with roughened plates as discussed in appendix A. Corrosion-inhibiting epoxy paints with desired glass-like surfaces have been proposed by a Norwegian Company.[47] Very frequent hull cleaning would be required in this system. Such a system does not appear to meet Navy readiness requirements.

CATHODIC PROTECTION/PERIODIC HULL CLEANING

Extended observations of inactive ships under cathodic protection at normal current densities have disclosed that fouling accumulations do not adhere well to hull surfaces thus protected. The technology of cathodic protection of ships has advanced to a sophisticated stage where impressed current systems[48,49,50] can be designed to prevent underwater corrosion on ships. If fouling adherence on active ships could be minimized by a combination of cathodic protection and periodic underwater cleaning, it would suggest the possibility of developing a system to supplement toxic antifoulant paints. Study of the feasibility of this concept is planned.

Another scheme, the use of high-current-density cathodic protection to provide an exfoliating calcareous surface to which fouling is attached with subsequent reduction of current density to maintain corrosion protection during periods of fouling build-up is discussed in appendix B. This scheme has suggested the use of electrocoatings according to the method of Cox.[61,62] Although its technical feasibility was demonstrated,[63] Cox's method was never implemented. Initial current requirements for a ship's hull were very large (1 A/ft$^2$). Also, there was the possibility that high strength steels used in naval construction would be susceptible to embrittlement by the hydrogen which would be developed electrolytically as a result of the cathodic process. The scheme may still have merit for fouling prevention of small, vital surfaces.

PAINT TOUCHUP UNDERWATER

As stated previously, AF and AC coatings have been damaged during hull cleaning operations, especially where fouling accumulations have reached an advanced stage of growth. Where such paint breakdown is caused, it is useful to be able to restore or touch-up affected areas without resorting to drydocking. Several paint formulations and application methods have been developed[64,65] which permit a diver to apply touch-up paint to the hull underwater. The relationship of underwater hull painting with compatible materials, methods for paint repair, and underwater hull cleaning merit investigation.

In this connection it should be noted that docking block areas on the hulls of ships which have been drydocked are vulnerable areas of fouling and corrosion. Normal practice requires that docking block position be shifted at successive dockings so that some paint maintenance is given to areas previously masked. This procedure precludes proper antifouling protection. The possibility of underwater painting of the docking block areas immediately after undocking appears to be an attractive alternative.

AUTOMATED CLEANING

A reasonable step in the development of an integrated hull maintenance system would include an automated inspection and hull-cleaning operation resembling in part that of an automated automobile car wash. The concept envisions that as ships get under way, they pass through a floating wash system in which their hulls would be scrubbed. One example of this concept is described in a recent patent[66] (royalty-free license to the Government). An automated brush system reportedly is used for the periodic cleaning of the hulls of ferryboats.[67] Evaluation of the feasibility of automated cleaning systems appears desirable in order to determine if further development work may be warranted.

A review of other antifouling techniques which may have limited applicability for Navy ships, especially on small, critical or inaccessible areas such as sonar domes, sea chests, propellers, etc., is included in appendix B. Also those antifouling systems which are considered impractical and not worthy of further pursuit are summarized for information purposes.

## DEVELOPMENT OF A NAVY UNDERWATER FOULING REMOVAL, AND CONTROL PROGRAM

It has been shown above that underwater hull cleaning is a useful tool for fouling removal and control, especially when used in an integrated approach. The best procedures to be used, the criteria for deciding when cleaning is necessary and coordination with Navy ship operating practices remain to be determined. The plan for conducting these investigations includes two major elements:

- How to Clean. Determination of the most practical and cost-effective hull cleaning methods for Navy ships.

- When to clean. Determination of criteria for deciding when to clean a ship's hull.

With these solutions in hand, a practical Navy procedure for underwater hull cleaning can then be prepared. The research and development program to be undertaken at the Center to address these elements is briefly described in subsequent secti  is of this report and is shown diagramatically in figure 14.

### HOW TO CLEAN

Underwater removal of fouling entails the use of diver-operated mechanical equipment that must be capable of dislodging a variety of fouling organisms without damaging the intact AF/AC paint system on the hull. The cleaning procedures must permit minor scouring of the AF paint surface to remove the spent outer layer (about 1 mil thickness) thereby exposing fresh AF paint on the rejuvenated hull surface. The equipment must be capable of operating on relatively flat surfaces of the hull as well as in recesses and on contoured appendages. The selection and operating characteristics of underwater cleaning equipment to perform these interdependent functions will require a field effort to determine practical capabilities of existing hardware and techniques.

A more detailed investigation on paint wear and rejuvenation characteristics of various AF paints in use or proposed will be conducted under laboratory controlled conditions. The critical parameters comparing the degree, effectiveness, and efficiency of fouling removal and/or control by various methods will also be examined more closely in the laboratory environment.

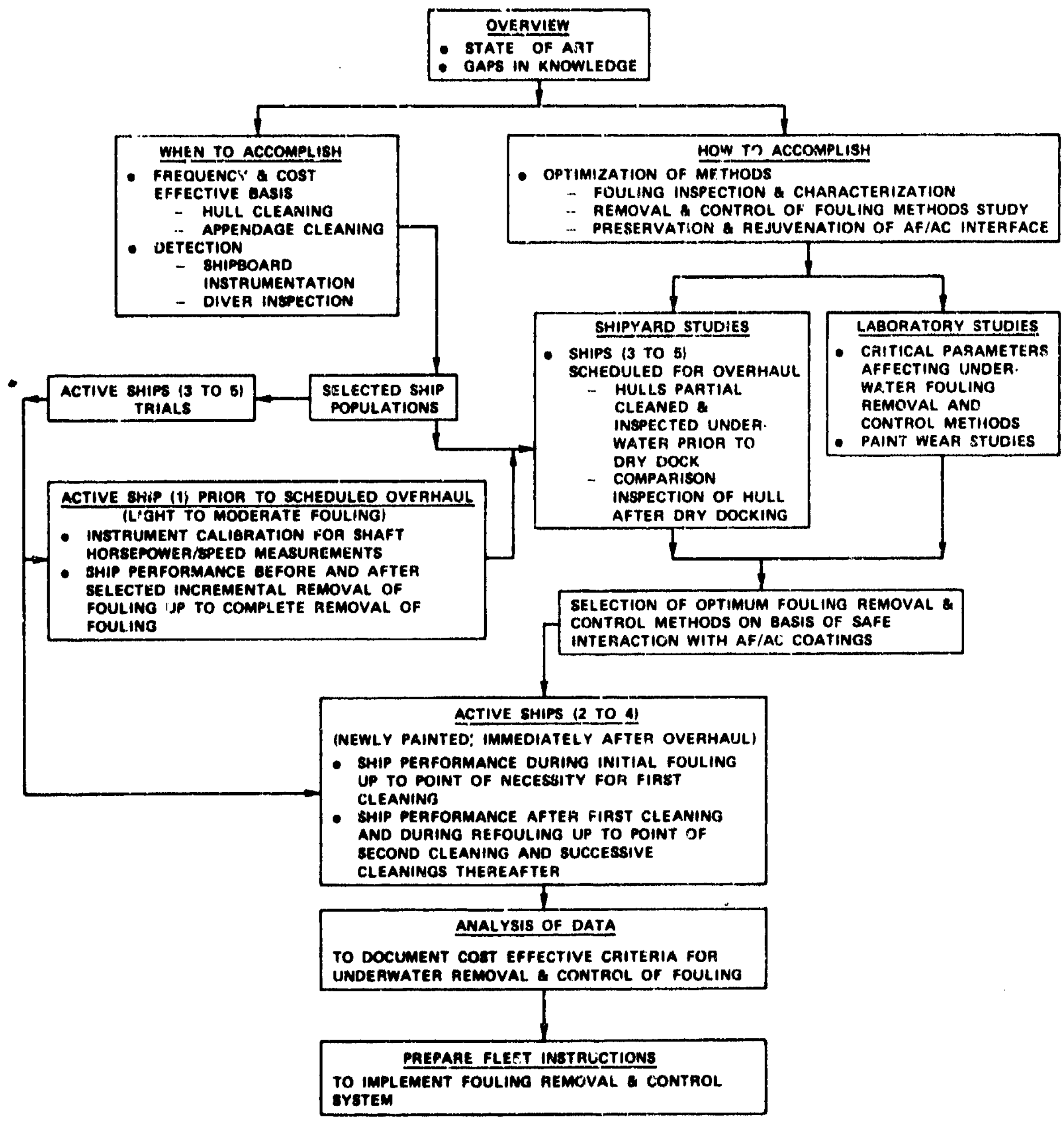



Figure 14
Fuel Conservation Through Underwater
Removal and Control of Fouling
Plan to Accomplish Objective

## Cleaning Methods Field Study

The field studies required to document and evaluate optimum procedures for underwater fouling removal are well underway. Navy shipyards and commercial contractors capable of performing underwater cleaning have been identified. Experience with, and cost and efficiency of previous underwater cleanings will be documented. Selected cleaning methods will be compared and evaluated.

With the assistance of NAVSEC, specific shipyards have been selected for participation in this phase of the program. Ship availability schedules for inspection and cleaning have been obtained. Ships having a wide range of fouling severity are being selected for inspection and cleaning. Work requests have been issued to arrange for underwater inspection of fouling of designated ships by DTNSRDC divers and those of cooperating shipyards. Requests have been made to implement underwater cleaning of selected areas of ships' hulls and appendages by designated procedures and to compare underwater with drydock observations of the appearance of the fouled and cleaned portions of the hulls. The effectiveness of selected cleaning procedures will be determined, including their compatibility with the AF/AC coating system. The severity of fouling that can be safely removed repeatedly with minimum damage to the AF/AC coating by existing in situ cleaning methods will be determined. Economics of the processes will be evaluated. Interim cleaning instructions will be prepared after a sufficient number of ships have been partially cleaned and inspected and the results compared with paint wear studies in the laboratory.

## Related Laboratory Investigations

Plans have been formulated and preparations are underway to conduct systematic supplemental laboratory investigations.

Equipment required to compare and evaluate various underwater cleaning methods (brushes, jets, etc.) will be procured. Factors for optimum cleaning efficiency will be identified.

Paint wear caused by brush cleaning of test panels exposed at Pearl Harbor and Miami fouling test stations will be evaluated, taking into account significant variables. The influence of cathodic protection on the removal of fouling and paint life will be investigated.

The effectiveness of supplemental noncoating, antifouling techniques (control of light, water salinity, gas generation) for specialized application to hull openings and appendages will be considered for further study.

Underwater Inspection

An essential second input to the decision on how to clean is an inspection rating of fouling of the underwater hull by divers. Such inspections would be useful after cleaning, also, to assess the effectiveness of the process as well as the effect of the cleaning on the paint system. The underwater inspections will serve the following purposes:

- Selection of a Cleaning Method. Fouling on a ship's hull varies with respect to the severity, types, location, and distribution of growths. As mentioned previously, it is more difficult to remove barnacles than slimes or grasses. A rational basis for characterizing fouling on the basis of severity, types, location, and distribution of growths will assist divers in the selection of appropriate cleaning methods.

- Effect of Cleaning on the AF/AC Coating System. The method of cleaning that is selected should have minimum adverse impact on the subsequent performance of the AF/AC system. A judicious hull maintenance program would include cleanings scheduled at intervals such that only mild wiping, brushing or washing would be required to strip off readily removable slimes and grasses. Such cleaning would be unlikely to damage the AF/AC system and indeed could rejuvenate a partially depleted AF coating by removing the depleted surface layer. On the other hand, vigorous cleaning required to remove established barnacles (intervals between successive maintenance cleanings are too long) could damage the AF/AC coating system.

- Cost and Time to Clean. Fouling characteristics can be related to anticipated cleaning costs and time required to clean. They can assist in defining criteria for use in contract negotiations for underwater cleaning services.

Individual cleanings should be viewed not as one time events but as parts of a system which involves periodic removal of fouling without adverse impact on the protective function of the AF paint. A cleaning schedule will be established to define the tradeoff point among such factors as cost of cleaning, paint life, and fuel savings.

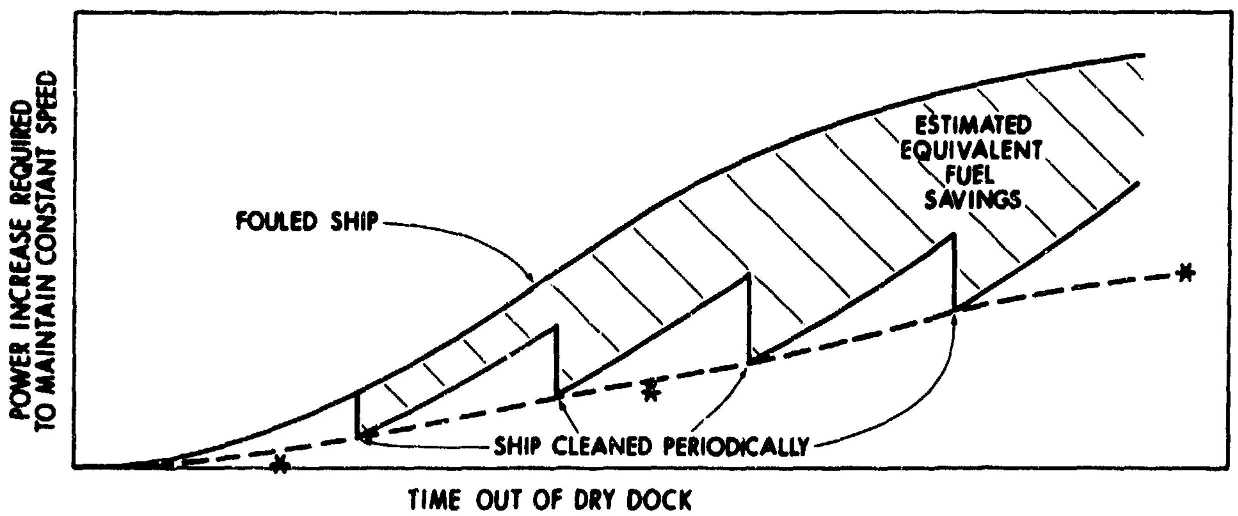
Considerable experience with underwater hull inspection has been acquired by the DTNSRDC diving team which uses sophisticated underwater photography equipment for both still and motion pictures.[68] The team has made underwater inspections of more than 20 ships to determine the severity of fouling and the need for underwater repairs. The divers have freed fouled air passages of underwater hull appendages. They also have removed major debris from sea chests and have cleared fouled propellers as required.

WHEN TO CLEAN

Since the purpose of underwater hull cleaning is fuel conservation, measurement of fuel consumption under standardized conditions would be the most direct method. However, the many variables of proper plant operation make such standardization difficult. A more practical approach is to measure hull drag increase, as shown by changes in the ship-speed/shaft-horsepower relationship (under standardized conditions), provided that sufficiently sensitive measurements can be made.

It is planned to conduct sea trials on three to five ships to ascertain quantitatively the effects of fouling removal on improved fuel economy. The initial sea trial will be performed on a lightly to moderately fouled ship scheduled for imminent overhaul to determine the capability of shipboard instruments to measure small changes of drag associated with incremental removal of fouling on the hull and appendages. While instrument calibration and repeatability are being checked, an opportunity will be afforded to separate the resistance changes caused by the fouling of the propeller and sonar domes as distinct from the hull. Also, the gross effects of fuel consumption before and after fouling removal will be determined as base line data.

Using drag measurement information due to fouling and its removal developed during trials for the first ship combined with diver inspection experience for characterizing fouling, it is planned to conduct additional sea trials on two to four newly painted, recently overhauled ships which will be deployed in different geographical areas. In these tests it is planned to develop data to determine the cost-effective frequency of periodic underwater fouling-removal consistent with fuel savings and optimum effectiveness of the paint over its service life. Figure 15 is a conceptual curve of these data which are to be sought. It can be seen in the figure that power increases as a function of time out of drydock due to fouling of the hull and propeller. By periodic cleaning, at the optimal frequency (to be determined), it is feasible to remove fouling growths with minimal disturbance to the paint system and thus restore the ship to its new base line of roughness with a slow increase of base line roughness due to corrosion and normal paint deterioration. The shaded areas under the curve in figure 15 is an estimate of the equivalent fuel savings.




*Represents power increase required to overcome increase in hull roughness attributable to deterioration of the AF/AC coating and to corrosion of the hull.

Figure 15
Conceptual Fuel Savings Versus
Frequency of Underwater Hull Cleaning

In order to obtain the data conceptually shown in figure 15, it will be necessary to measure changes in shaft horsepower, Ps, before and after hull or propeller cleaning at a given speed, V, and relate these measurements to changes in total ship resistance, $R_T$, or changes in the propulsive coefficient $\eta$, (a measure of how efficiently the shaft horsepower is converted into effective horsepower for propelling the ship.) The shaft horsepower, Ps, will be determined by accurate torque and revolutions per minute measurements taken during the planned trials. The relationship of these parameters is shown in the generalized equation:

$$\frac{Ps}{V} = K\frac{R_T}{\eta}$$

where K is a proportionality constant. The propulsive coefficient of a ship with a clean undamaged propeller will be assumed to be equal to the value determined from model tests. Any power change at a given speed measured for a ship before and after cleaning the propeller will be ascribed to change in the propulsive coefficient with the assumption that the total resistance remains constant. Further changes in power for a given range of speeds due to additional hull cleaning (propeller in cleaned condition) will be related to changes in the total resistance. Both changes will be related by fuel usage measurement to corresponding changes in fuel consumption. The effect of the hull cleaning on $\eta$ although not determined will be included in the change of $R_T$ for purposes of considering fuel savings resulting from hull cleaning. Detailed procedures for conducting standardized trials are described elsewhere.[20]

## FLEET INSTRUCTIONS AND IMPLEMENTATION

At the conclusion of the program, as shown in figure 14, cost-effective criteria will be available to help determine the optimum relationship between frequency of cleaning and fuel savings, utilizing the 5-year intervals between ship drydockings. Through appropriate commands and with the approval of Superintendent of Diving, DTNSRDC will document for Fleet use final instructions for optimum underwater hull cleaning methods and frequency. DTNSRDC is seeking approval by and assistance from CNO and cognizant commands for these segments of the program, as required.

## CONCLUSIONS

It is concluded that:

- Underwater hull cleaning methods are available for effective removal of fouling growth. Current information indicates that brush methods are leading contenders.

- Investigation is warranted and is underway to determine the impact of cleaning on the life and performance of AF/AC paint systems.

- On the basis of preliminary estimates, underwater hull cleaning is a cost-effective method for removal of fouling from the hulls of Navy ships. A total fuel savings, conservatively estimated, of 10% is attainable. Evaluation of available methods is necessary to select those most suited for removal of fouling while retaining and improving subsequent AF effectiveness on Navy ships.

• An investigation is necessary and is in progress to establish tradeoffs weighing maintenance cost versus fuel cost savings considering such factors as cleaning methods, cleaning schedules, and ship performance on the basis of the intervals currently imposed between ship drydockings.

• It is envisioned that interim hull cleaning procedures can be introduced into the Navy within the next 2 years based on the program currently underway at the Center.

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## APPENDIX A

## HYDRODYNAMIC ASPECTS OF SHIP PERFORMANCE AS AFFECTED BY FOULING

### INTRODUCTION

The information contained in this appendix presents the rationale for determining increases in frictional drag of ships by fouling and the effects of fouling on the propulsive efficiency of propellers. The method of obtaining the data, as plotted in figure 4 of the text, is developed more fully.

### SCALING EFFECTS

Scaling techniques for predicting total ship resistance at full-scale from model experiments have been fairly well developed and involve measuring the force required to tow a geometrically similar model at full-scale Froude numbers. Techniques to predict frictional resistance at full-scale Reynolds numbers are available; these semi-empirical methods are based on studies of turbulent flow over smooth flat plates.

Some attempts have been made to devise methods for scaling roughness by converting random roughness on a surface to an equivalent sand roughness[1,2,3] (geometrically defined) and relating the height of that roughness to the thickness of the boundary layer[4,5] of water immediately adjacent to the surface moving through the water.

Experiments to measure the thickness of boundary layers on ship hull surfaces have met with limited success.[6,7] Roughness scaling is not an exact science at present. However, in one recent model friction plane study it was found that the roughening of ship plate attributable to corrosion and repetitive sandblasting over an 11-year period increased the coefficient of friction by an order of magnitude over that of a smooth clean plate.[8] The results of this study are not directly applicable to full size ships since roughness scaling was not considered.

[1] Superscripts refer to similarly numbered entries in the Technical References at the end of this appendix.

At present, roughness allowances are added to correct frictional drag at full scale. These roughness allowances are determined from standardization trials which account for plate, structural, coating, and fouling roughness. Roughness allowances can be determined from analysis of previous data obtained by others and supplemented by trials planned for selected ships.

FOULING ROUGHNESS OF SHIPS

McCarthy[illegible] treated the effects of hull roughness and fouling on frictional drag of ships within the framework of current knowledge as follows:

> "The total resistance coefficient, $C_T$, of a ship is defined by $C_T = R_T/\frac{1}{2}\rho V^2 S$ where $R_T$ is total resistance, $\rho$ is mass density of water, V is ship speed, and S is total wetted area. In predicting the full-scale calm-water resistance of a "newly-built" ship from model resistance data, it is customary American practice to introduce three components of resistance coefficients:
>
> $$C_T = C_F + C_R + C_A$$
>
> Here, $C_F$ is a computed empirical frictional drag coefficient of a smooth plate having the same length, speed, and wetted area as the ship, $C_R$ is the residual (or wavemaking and form) resistance coefficient usually deduced from model resistance data (subscript m) on the basis of the Froude assumption[10]: $C_R = (C_R)_m = (C_T)_m - (C_F)_m$ and finally $C_A$ is the correlation allowance or an "added" resistance coefficient,* which insures that measured and predicted full-scale speeds are equal for a given shaft horsepower (SHP) or thrust. Different

---

*In some works on the subject, correlation allowance is given the designation, $\Delta C_F$, to indicate that the "added" resistance may be considered in terms of an equivalent added frictional resistance. While this designation is permissible, it can be physically misleading, because $C_A$ includes some form drag as well as other effects.[11]

values of $C_A$ can result depending on whether correlations are based on thrust or torque (SHP) measurements.

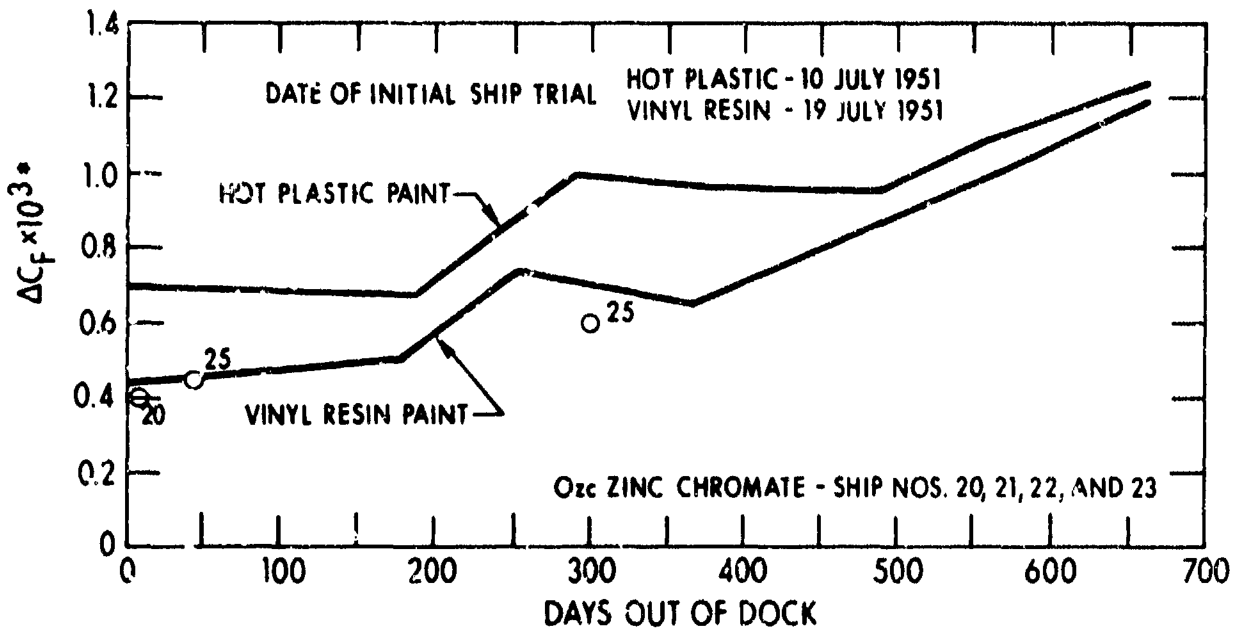
The new-ship allowance coefficient, $C_A$, is an empirically-determined correction to the predicted full-scale ship resistance, which takes into account surface roughness, waviness, miscellaneous small protuberances, and hull openings which are not simulated in model-scale experiments. It also allows for ill-defined hydrodynamic scaling effects associated with different experimental facilities, analysis techniques, model turbulence stimulation methods, and differences in model-ship hull boundary layer flows; experimental errors or biases at model scale and full scale; and propeller shaft friction effects which can influence both model and full-scale trial data. Analysis of full scale trial data at NSRDC, using the International Towing Tank Conference (ITTC) 1957 friction line, indicates that for most ships the type of paint used is the most important factor affecting the value of $C_A$. For Navy vinyl Paints, $C_A$ averages about 0.4 to 0.5 x $10^{-3}$.

In addition to the correlation allowance which must be made in order to predict new-ship resistance from model test data, there are a number of environmental and deteriorative factors which can degrade ship resistance and propulsion characteristics over a relatively short period of in-service operating time. Environmental factors include performance degradation due to ocean waves, winds and currents; deteriorative factors include hull and propeller fouling, corrosion, erosion, and wearing down of propulsion machinery and subsystems.[1a]"

POWER INCREASES

For purposes of this report, the deteriorative factors of major significance are considered to be hull and propeller fouling. For roughness increases due to hull fouling, an increment $\Delta C_F$ is added to $C_F$ for the newly built ship.

On the basis of their field studies, Hadler et al[11] demonstrated a relationship between the increase in frictional drag, $\Delta C_F$, of four destroyers, two painted with Navy Hot Plastic systems (20 and 21) and two painted with Navy Standard, Vinyl (22 and 23), as shown in figure 1-A. Results of trials are also included for ship 25 which was tested twice with vinyl resin paint and belongs to the same destroyer class as the other four ships.




*On the basis of standards adopted at the International Towing Tank Conference, 1957.

Figure 1-A
Effect on $\Delta C_F$ of Time Out of Dock for Hot Plastic and Vinyl-Resin Paints from Correlations of Ship Nos. 20, 21, 22, 23, and 25

By linearizing the trials information shown in figure 1-A, it is possible to estimate the power loss of destroyer type ships as follows:

The Reynolds number for a typical destroyer cruising at 20 knots is of the order of $5 \times 10^8$. The frictional drag coefficient for this typical destroyer is $1.7 \times 10^{-3}$ on the basis of Schoenerr's mean line for turbulent flow over smooth planks[13] which was adopted at the ATTC 1947 conference. This value is substantially the same as that given by Gerber's formula[14] which was adopted in 1957 at the ITTC conference. To the above value is added the hull correlation allowance, $C_A$, of approximately $0.45 \times 10^{-3}$ as measured for destroyers having the vinyl paint systems (see figure 1-A) giving a total of $C_F + C_A = 2.15 \times 10^{-3}$. The $\Delta C_F$ for fouling is taken from figure 1-A at $0.8 \times 10^{-3}$ for vinyl systems after 660 days out of dock. This provides the ratio

$$\frac{\Delta C_F}{C_F + C_A} = \frac{0.8}{2.15} = 0.37 \quad .$$

At cruising speeds (15 to 20 knots) more than half the power to propel a surface ship is used to overcome frictional drag.[9] The remainder of the power is used to move water around the hull with its consequent wave-making resistance. At a given speed, power is proportional to total resistance. Therefore, a 37% increase in frictional resistance which affects about half the power required to propel the ship requires an increase of 18.5% in power to maintain speed. This estimated power increase falls within measurements made on other ships as reported by Stenson.[15]

The power increases resulting from fouling roughness on propellers, as discussed briefly on pages 8 and 9 of the text, are even more significant than those ascribed to hull fouling. The individual effects of fouling of hull and fouling of propeller on ship performance and fuel consumption can be determined during ship trials. Measurements made before and after removal of fouling from each component should permit calculation of their individual contributions to ship performance and fuel consumption.

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## APPENDIX B

## FOULING PREVENTION TECHNIQUES

The information contained in this appendix provides insight into the mechanisms of antifouling action of coatings and means of rejuvenation of their surfaces. Also, noncoating methods of fouling control are reviewed and certain processes are identified for potential use on critical or inaccessible areas.

### COATINGS

The primary fouling prevention technique for hull surfaces is a hull preservation system consisting usually of a metal primer, anticorrosion coats, and antifouling topcoats. In addition to preventing hull corrosion, the anticorrosion coats serve as an insulating barrier which prevents galvanic corrosion promoted by the copper-base antifouling topcoats.[1] In order to understand the interaction between hull paint systems and the sea, it is well to review some of the more common toxic antifouling paint systems used by the Navy or under development and to be aware of the mechanisms whereby antifoulants function.

At present cuprous oxide dispersed in various resin and rosin matrices is the principal toxic component used in antifouling paint formulations.[2,3] Recently tributyl tin oxide (TBTO) has been incorporated into a carboxylated vinyl resin formulation to provide improved resistance to fouling by certain types of grasses.[4,5] Antifouling coatings rely on several mechanisms for release of the toxic to maintain a lethal layer at the seawater/paint coating interface in order to prevent and inhibit the attachment of fouling organisms.

### LEACHING OF TOXIC

The more effective antifouling paints include a high loading (85% to 95% by weight) of cuprous oxide dispersed in a polymeric matrix. Although cuprous oxide usually is considered to be relatively insoluble in water, it still is sufficiently soluble to leach slowly out of the paint matrix. Effectiveness of the paint is measured by its ability to maintain a minimum required leaching rate of toxic of approximately 10 $\mu g/cm^2/d$ to provide adequate fouling protection over a given service life.

---

[1] Superscripts refer to similarly numbered entries in the Technical References at the end of this appendix.

Physical factors that would improve antifouling paint performance with an extended life include increased paint thickness and maximum loading of the toxicant that would permit controlled dissolution of the toxic while still maintaining the integrity of the paint. In the past, thick matrices heavily loaded with toxic (hot plastic systems, Navy formula 15 hp) would erode slowly and expose new layers of embedded toxicant. These fomulations afforded a long antifouling life (up to 3 years during World War II), but the coatings initially were rough, porous, and soft and as they aged they became more susceptible to physical damage.

DIFFUSION-DISSOLUTION OF TOXICANT

An elastomeric matrix can be formulated so as to incorporate an organic toxic compound in solid solution which permits a more uniform and sustained release of the toxic.[6,7] The concentration of the toxic in the surface layer would tend to become depleted because of its continued, slow release. However, the required surface concentration of the toxic is maintained by continuous replenishment of the toxic diffusing through the matrix. Thus, thicker coatings would provide a larger reservoir of toxic, thereby extending the service life of the paint.

At present these systems are somewhat specialized, and their application is restricted to relatively small patches on vulnerable components of high performance ships. Furthermore, it appears reasonable to expect that smooth, resilient elastomeric coatings should be ideal surfaces for programmed cleaning, because such coatings would resist physical or mechanical abuse more readily than conventional plastic resins.

HYDROLYSIS OF TOXICANT

An organometallic toxicant can be chemically bound with a suitable polymer to form a coating whose toxic release is triggered by surface hydrolysis in seawater.[8,9,10] The chemically bound toxic is depleted at a controlled rate contingent on the type of polymer backbone, the degree of crosslinking, and the degree of substitution along the polymer backbone. The depletion mechanism is not fully understood. However, because of very low leach rates associated with these organometallic polymers, it is believed that surface depletion is mainly dependent on mechanical or biological removal of the hydrolyzed layer and only slightly dependent on solubility in seawater. These antifouling materials may show depletion rates that are insensitive to fluid velocity and therefore may retain toxicity for longer periods on ships underway. The mechanism of leaching and means for measurement under simulated hydrodynamic conditions is a subject of further study at this Center under another segment of the Navy Energy Conservation Program.

## AUXILIARY ANTIFOULING TECHNIQUES

In addition to the control of fouling by suitable paint coatings, several other methods capable of rendering the immediate environment hostile or lethal to various types of fouling organisms have been discussed in the technical literature. A list of these methods, which have limited applicability for Navy ships, is shown in table 1-B.

TABLE 1-B
SUPPLEMENTARY ANTIFOULING TECHNIQUES FOR POTENTIAL USE IN COMBINATION WITH ANTIFOULING PAINTS AND/OR PERIODIC UNDERWATER CLEANING

| Method | Means | References | Limitations of Method |
|---|---|---|---|
| Water movement | Rotation, pumping, gas generation at surfaces | 11, 12, and 13 | Must be confined to relatively small areas such as propellers and sea chests |
| Surface texture | Smooth surfaces | 14 and 15 | Not effective by itself but may augment effectiveness of AF paints and reduce frictional drag of fresh coat systems |
| Light and illumination | Color of surfaces exclusion of light | 16 | Reduces the incidence of attachment of certain fouling organisms and can augment effectiveness of AF paints on rate of accumulation between underwater cleaning periods |
| Exfoliation | Cathodic protection | 17 | Limited to small areas; bond strength of barnacle attachment reduced for easier removal by auxiliary cleaning methods; augments corrosion protection of deteriorating paint systems |
| Freshwater incursion | Maintenance of laminar sublayer of lower salinity | 18 | Inhibits attachment and growth of certain species of fouling; flowing systems must be confined to relatively small surfaces (propellers); must be used with retaining skirt for large areas of hull; augments effectiveness of AF paints |
| Toxic fluids | Chlorination | 19 and 20 | Potential use limited to confined areas such as propellers, sea chests, and closed systems* |

*A commercially available device for the generation of chlorine gas by electrolyzing seawater is being investigated by NAVSEC for the control of fouling in sea chests and main condensers.

Several other antifouling techniques which have been reviewed are considered impractical for the reasons indicated in table 2-B.

TABLE 2-B
AUXILIARY ANTIFOULING TECHNIQUES CONSIDERED
UNSUITABLE FOR NAVY USE

| Method | References | Reason for Rejection |
|---|---|---|
| Radioactive isotopes | 21 | Did not prevent barnacle growth. Low order of radioactivity stimulated growth of some species. |
| Ultrasonics | 22 | Area of action confined to very small areas. Vibratory motion erodes materials. |
| Heat | 23 | Technically feasible, but power consumption prohibitive. |
| Alternating current | 23 | Ineffective in preventing larvae attachment, field of action for causing tetany or protein coagulation extremely limited. |
| Air bubbles (water movement) | 24 | Impractical for ship hulls; excessively large volumes of air are required. |

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