A FINAL REPORT ON

MARINE FOULING AND UNDERWATER HULL CLEANING IN SAN DIEGO BAY

by

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INTRODUCTION:

Antifouling (AF) paints are used on vessel bottoms and other submerged surfaces to inhibit the attachment and growth of biological organisms. AF paints have biocides which are dispersed within the paint and released by various mechanisms to the paint/ water interface, where fouling takes place. These biocide-containing AF paints are effective at slowing the fouling process, but can neither prevent nor arrest it completely. It is necessary to physically remove these organisms from vessel bottoms periodically, usually while the vessel remains in the water. This practice is known as underwater hull cleaning (UWHC) and is performed by divers who use various materials and tools to wipe, scrub, and/or scrape fouling organisms from the surface to be cleaned.

UWHC removes paint chips and abrades the surface of the AF paint which increases the rate at which biocides are being released into the environment. This practice might have a significant negative impact. This paper will present an overview of marine fouling, antifouling paints, antifouling biocides, and what is known about UWHC practices. It will also attempt to characterize the impact of hull cleaning on a large estuarine harbor such as San Diego Bay.

Purpose

The paucity of information regarding UWHC practices makes it difficult to assess the impact on the environment. In order to obtain information on UWHC and attempt to characterize its practice in San Diego Bay, a survey was developed by California Regional Water Quality Board (RWQCB) staff. The survey collected information from four discrete groups who were thought to have information about UWHC: 1) underwater hull cleaners; 2) marine businesses; 3) the U. S. Navy; and 4) individual boat owners.

The primary objectives of this survey were to determine: 1) how much UWHC is being done in San Diego Bay; 2) who performs UWHC; and 3) what techniques are being used in UWHC operations? This survey was also designed to ascertain the perceived benefits and impacts of UWHC.

Secondary objectives of the survey were to discover: 1) how often are vessels cleaned in the water versus being hauled out of the water and cleaned on land; 2) how often are vessels painted; and 3) what kinds of paints are used on hulls in San Diego Bay? Finally the question of whether all concerned groups are in agreement about the scope and practice of UWHC in San Diego Bay must be addressed.

LITERATURE REVIEW:

San Diego Bay:

San Diego, California, is located in the extreme southwest corner of the United States. **San Diego Bay** is an important commercial and recreational characteristic of San Diego. The Bay is about 15 miles long and ranges from one-fourth to two and one-half miles across. Its surface area is approximately 18 square miles and its volume about 300 million cubic yards. Tidal flushing maintains a deep channel at the mouth of the Bay and to some extent in the narrower north Bay where the average depth is about 35 feet at mean lower low tide. The wider south Bay is more shallow and requires periodic dredging to maintain the ship channel. The average depth in the south Bay is about 10 feet at mean lower low tide (Peeling, 1974).

San Diego Bay has mixed tides with the average difference between the mean higher tide and the mean lower tide at about 5.50 feet up to an extreme of 9.50 feet. This difference, the tidal prism, represents an average of 100 million cubic yards, or about one third of the Bay's total volume. Tidal currents are strong in the deep narrow north Bay and much weaker in the shallow south Bay (Peeling, 1974).

San Diego Bay is today best described as a predominantly marine estuary, although it was a mixed estuary in its pristine state. Human activities, most notably the diversion of the San Diego River to the north and the damming of the Otay and Sweetwater Rivers inland, have cut off virtually all fresh water flow to the Bay. Runoff from infrequent rains and discharges from private and commercial activities are the only significant sources of fresh water to the Bay now (Peeling, 1974).

The climate in San Diego is described as moderate and dry. The mean air temperature is approximately 60 degrees Fahrenheit and the water temperature ranges from 57 to 75 degrees Fahrenheit (Peeling, 1974). The area receives less than 10 inches of precipitation annually on average (Peeling, 1974). Because of the climate, most activities can be done year round, including boating and other water activities.

Except for a few areas of mud flats in the south Bay, and several small parks located around the Bay, the entire shoreline is occupied by various human activities with high potentials for pollution. The U.S. Navy occupies the greatest percentage of the bayfront. Most of Coronado Island is part of the North Island Naval Air Station. A submarine base, its support activities, several training facilities and the Naval Oceans Systems Center occupy Point Loma. Naval Station San Diego, home to a substantial portion of the Pacific fleet, is on the east side of the Bay, directly across from the Naval Amphibious Base on the Silver Strand to the west. In all, the San Diego area supports more than 80 separate commands on 10 large facilities. In addition, 86 Navy vessels are permanently home-based in San Diego (Phone contact April 1991, Public Affairs Office, N.S., S.D.). There are over 100,000 active duty personnel in San Diego and more than 300,000 reservists, retirees, and dependents (Phone contact April 1991, S.D. Chamber of Commerce).

The industries located on the Bay can be divided into three categories: 1) miscellaneous, 2) aerospace, and 3) maritime (S.D. Interagency Panel, 1989). The miscellaneous category includes facilities like the power generating plants in the south Bay. There are several aerospace industrial facilities adjacent to San Diego's commercial airport near Harbor Island, and there is another large aerospace industrial facility on the east side of the south Bay. The maritime industry revolving around San Diego Bay consists of large ship repair facilities or shipyards, small vessel repair facilities or boatyards, marinas and docks, and dozens of auxiliary operations such as sail shops, boating hardware shops, fueling facilities, pump out facilities, and nautical supplies wholesalers and retailers. The industries lining the Bay have become part of the environment of the Bay and must be factored into any ecological consideration.

Marine Fouling:

Fouling refers to the growth of various marine organisms on submerged surfaces. Fouling organisms commonly found in San Diego Bay include the tube-building polychaete worms or "tube worms," encrusting bryozoans or "moss animals," algae, small sponges, tunicates, barnacles, and other sessile organisms (Johnston, 1990). Fouling can be seen on any surface that has been submerged in the Bay for 10 days or more, and can grow to a substantial bulk if left undisturbed for a prolonged period of time.

Fouling Progression:

Fouling appears to follow a general progression of colonization on submerged surfaces. According to Wahl (1989), from whom the following description is taken, this fouling progression is characterized by four fairly distinguishable phases: 1) biochemical adsorption; 2) bacterial colonization; 3) unicellular eukaryotic colonization; and 4) multicellular eukaryotic colonization.

1. Biochemical adsorption: Biochemical conditioning begins as soon as a surface is submerged. Dissolved chemical compounds (primarily glycoproteins, proteoglucans, and polysaccharides) in the sea water are electrochemically attracted to the newly introduced surface. Adsorption of these compounds reaches an equilibrium about 1 hour after emersion of the surface, at which time bacterial colonization begins (Wahl, 1989).

2. Bacterial colonization takes place over a period of days and is best described by looking at the process by which a single bacteria colonizes the surface. The physical forces of currents and turbulence bring the colonizing cell very near the surface to be colonized, Brownian motion and microturbulence move the cell closer still to the surface. At this point, both the surface of the cell and the macromolecules covering the submerged surface are negatively charged and tend to repel each other. The cell then produces fibrils that attach to the biochemically conditioned surface and pull the cell in, allowing it to attach firmly and begin to proliferate. This phase will not attain an equilibrium, due primarily to the transitory nature of bacterial populations (Wahl, 1989).

3. Unicellular eukaryotic colonization begins several days after immersion and involves colonization by unicellular euceryotics such as yeasts, protozoa, and diatoms, with diatoms being the dominant colonists and having the greatest subsequent impact on the submerged surface. These unicellular euceryotics, their bacterial counterparts from the previous phase, along with all of the secretions and decay materials produced, comprise the slime layer or primary film that covers virtually every exposed surface in the sea (Wahl, 1989).

4. Multicellular eukaryotic colonization: The settlement of multicellular organisms on the submerged surface comprises the fourth phase of the fouling progression. Depending on the biological activity of the water around the submerged surface, macrofouling can begin as early as several days up to weeks after immersion. At this stage, the surface will usually be supporting a well differentiated microbiotic community with a three-dimensional structure. Upon this base, mesoplanktonic larvae and algal spores begin to settle. This process overlaps with continued recruitment and evolution of the microfouling community. From this point on, the fouling community continues to grow and evolve and may be influenced by such factors as

disturbance, facilitation, inhibition, and tolerance (Chalmer, 1982; Wahl, 1989).

There is still some question as to whether this apparent progression of fouling from biochemical adsorption to macrofouling is indeed a sequential progression, or if it can be explained by other mechanisms. Wahl (1989) postulates that the relative abundance of a particular organism combined with its growth rate and general adaptability may determine its relative abundance on a surface at a given time after immersion. For instance, the macromolecules in the first phase of the progression are omnipresent in sea water and would logically be the first to make contact with a new surface. Bacteria are also very abundant, have excellent adaptation mechanisms, and have considerable reproductive "speed." Diatoms are still quite plentiful, but not in numbers comparable with bacteria, nor do they have the reproductive capabilities of bacteria. Finally, the spores and larvae of multicellular organisms are relatively rare and may be restricted to reproductive seasons (Chalmer, 1982). This gradation of availability may be solely responsible for the "progression" of the fouling process.

It is also possible that there may be certain properties of the "conditioned" surface which attract later colonists. Factors such as texture, color, and certain exudates from bacteria and diatoms may provide cover, food, or other commodities to later arrivals. To date, many studies have been done which have attempted to clearly show whether the fouling progression is a chronologically or causally determined sequence, but none have been conclusive. Wahl (1989) states: "It is possible that the apparent constancy of the fouling sequence is a result of the factors 'colonizer availability' and 'progressive surface conditioning' acting synergistically, however, the relative importance of these remains to be established".

This seems to support the conclusions of Dean and Hurd (1980) who showed that earlier colonists' propensity to inhibit later colonists is equal to or greater than that to enhance their establishment. They further state that the effect of this inhibition is more profound than any effects from enhancement.

Economic Importance of Fouling:

Fouling is an important consideration economically for any venture involving the sea. Even the microscopic primary film can cause enough drag to decrease a large vessel's fuel efficiency by 10% (Loeb, Laster, Gracik, & Taylor, 1984), and through one or more of several mechanisms (most commonly the formation of hydrogen sulfide), enhance the corrosion of metals in the marine environment (Gerchakov & Udey, 1984). The effects of macrofouling are even more impressive.

Added weight and drag from macrofouling can cost a single navy vessel over one million dollars in a 36-month period from increased fuel consumption (Preiser & Laster, 1981). Additionally, damage from corrosion, clogged sea water pumping systems and heat exchangers, plus cleaning and inspection costs can add substantially to that bill (Fischer, Castelli, Rogers, & Bleile, 1984; Rascio, Giudice, & del Amo, 1988). On another level, safety becomes an issue when navigational buoys are weighed down by fouling and positioned lower in the water (Fischer, et al., 1984). The implications of a slowed warship or a fouled sonar device in a crisis situation could be global in scope (Cologar & Preiser, 1984; Preiser & Laster, 1981; Scharzberg, 1987).

Fouling also puts a financial burden on owners of recreational craft. Aside from any increased fuel consumption, the average recreational boatowner spends about $700 per year on maintenance and repairs directly related to fouling. Multiplying this figure by the estimated 10,000 recreational vessels harbored in San Diego Bay yields seven million dollars per year, a significant contribution to the economy of the area.

Fouling Control:

Fouling control has been practiced for as long as there have been sea going vessels. The methods used have varied over the years, and even today different methods are used for different situations. This is because the fouling community on one type of vessel may be completely different from that on another type due to the different functions of those vessels.

Deep sea going vessels with very little in-port time, such as supertankers, are fouled primarily by algae because they are capable of attaching while the ship is underway at low speeds (Fischer et al., 1984). On Navy ships, the main fouling problem is from hard shell growth such as tube worms and barnacles because the softer fouling is washed away at high speeds (Cologer & Preiser, 1984; Fischer et al., 1984; Preiser & Laster, 1981). All types of fouling are important to recreational vessels because they are stationary most of the time (Fischer, et al., 1984).

The most common methods used for fouling control today are 1) chemical controls such as antifouling paint and 2) physical removal of the fouling by scrubbing.

Antifouling Paint:

A general description of antifouling (AF) paint might be a biocide component dispersed within a paint matrix which has some form of release mechanism. AF paint controls fouling by releasing a sufficient amount of toxic chemicals to the water/hull interface to kill or repel fouling organisms. There are two main categories of AF paints available for use today: **1) conventional AF paints** and 2) **self polishing copolymer (SPC) paints**, which are distinguished by the mechanism of release for the biocide component (Champ, 1986; Champ & Pugh, 1987).

Conventional AF Paints, which release biocide by simple dissolution in sea water, can be further divided into two release types: 1) contact leaching and 2) ablative. In **contact leaching paints**, the biocide is dispersed within the honeycombed channels of an insoluble paint matrix. When the paint is newly applied, the soluble biocide completely fills the insoluble matrix. Upon contact with sea water, the biocide immediately begins to dissolve and flow out of the matrix. The leaching of the biocide is driven by diffusion along concentration gradients within the channels of the matrix. As the distance the biocide must travel to the surface of the paint increases, the actual leach rate decreases. One major implication of this is that the initial leaching rate from fresh contact leaching AF paint must be much higher than that required to control fouling so that it can remain effective over long periods in the water.

Another implication is that a substantial amount of undissolved biocide remains deep within the matrix after the paint has become ineffective. This spent matrix, and the unused biocide it contains, must be removed before new paint can be applied, making it a hazardous waste that must be dealt with by the boatyards and shipyards (Bowmer & Farrari, 1989; Caprari, Slutzky, Pessi, & Rascio, 1986; Champ, 1986; Champ & Pugh, 1987). The old contact leaching paint must be removed for two reasons: first, the hull surface must be absolutely smooth for new paint application and contact leaching paints are usually pockmarked and rough after the biocide has leached out; second, different formulas of paint may have incompatible bases, even if they are the same brand (Gladstone, 1989).

In **ablative paints**, also called soft sloughing paints, the soluble biocide is mixed with a paint base that is also soluble. When ablative paints are immersed in sea water, both the biocide and the paint base begin to dissolve. As this takes place, the thickness of the paint decreases until none remains on the hull (Rascio et al., 1988). This would imply that nearly all of the paint applied to a boat would be released to the environment, and again, any paint removed from the vessel before painting would contain biocide. An interesting point is that over the lifetimes of the two types of conventional AF paints, the leach rate of ablative paint is about 50% higher than that of contact leaching paint (Caprari et al., 1986).

Ablative paints are often preferred by operators of commercial fishing vessels and work boats for several reasons: it is the least expensive type of paint; these vessels are slow moving and do not require a hard hull finish; most of these vessels are hauled out once or twice a year anyway so the short paint life is not a problem; the high biocide content makes ablative paint very efficient for short periods; and, finally, ablative paints do not have to dry or cure so a freshly painted boat can be launched immediately (Gladstone, 1989).

Self Polishing Copolymer Paints are relatively new and have a completely different release mechanism. In these paints the biocide is actually a component of the paint binder in the form of an acrylic resin and biocide copolymer. This paint is initially insoluble, and sea water never enters the paint matrix. When immersed in sea water, a hydrolysis reaction takes place on the paint's surface breaking the biocide away from the resin. This initial layer soon erodes away and exposes a new surface where the reaction is repeated. This hydrolysis-erosion cycle continues until the paint is gone. An important advantage of SPC paint is that the manufacturer can control the rate of the hydrolysis reaction and therefore the biocide release rate. Another advantage is that any paint remaining on the vessel does not have to be removed before repainting. Because SPC paint actually gets smoother as it wears, any remaining SPC paint, once thoroughly cleaned, is an excellent base for new SPC paint application (Champ 1986; Champ & Pugh, 1987; Gladstone, 1989).

Biocides Used in AF Paints: There have been many chemicals used as biocides in AF paints including mercury, lead, zinc, and cadmium (Champ, 1986). Presently, however, copper compounds and tributyltin (TBT) are the primary AF biocides in use (Champ, 1986). The differences between these two biocides are striking. Copper based AF paints have a shorter effective lifetime than TBT based paints; two to three years for copper compared to as many as seven years for TBT (Good & Monaghan, 1984). In addition, TBT may be as much as 100 times more effective than copper, based on an effective leach rate of .1 ug per square centimeter per day for TBT (Schatzbert, 1987) and an effective leach rate of > 10 ug per square centimeter per day for copper (Caprari et al., 1986). Toxicity comparisons between TBT and copper are difficult because of the impact of environmental factors such as pH, temperature, and alkalinity on copper toxicity (EPA, 1980; Flemming and Trevors, 1989).

AF Biocides in the Environment:

Biocides from AF paints generally enter the marine environment through one of three major routes: through the normal leaching process designed into the paints, through paint chips abraded from vessels' hulls in the water, and through paint or paint chips from blasting or painting operations which are dumped, washed, or blown into the water from shore (Stang, 1985; Johnston, 1990; California Regional Water Quality Control Board, Santa Ana Region, 1990; Barry, 1972; Coe & Michael, 1985).

The introduction of paint chips into the environment from boats being cleaned or repaired in the water is certainly a factor; whether or not this occurs frequently enough to create a problem is in doubt and will be discussed further in a later section of this paper.

Copper in the environment: Copper, though less toxic than TBT and consequently not as harmful to non-target marine organisms, may still pose a significant environmental threat because of the much larger quantities used in AF paints and its persistence in the environment. Copper is relatively soluble in water, and the chemical form taken by the copper once in the water determines its toxicity (U.S. EPA, 1992; Flemming & Trevors, 1989). Factors such as pH, temperature, alkalinity, and the concentrations of bicarbonate, sulfide, and organic ligands determine whether copper in the water will be ionic, complexed, or precipitated (U.S. EPA, 1980; Fleming & Trevors, 1989). Generally speaking, as the hardness, alkalinity, and total organic carbon in the water increase, the toxicity of copper in that water decreases (U.S. EPA, 1980).

From the above it can be seen that the total amount of copper in a body of water does not necessarily relate directly to toxicity. Bivalent compounds of copper with chloride, nitrate, and sulfate are highly soluble, and are easily converted into ionic copper (Cu^{++}) which is the most toxic form. Less toxic yet labile forms are created when copper is bound to hydroxides, carbonates, or sulfides. These forms are easily converted back to the ionic species by seemingly minute changes in the environmental factors mentioned earlier. When ionic copper is complexed with organic ligands, its bioavailability, and hence its toxicity, is reduced even more. Copper in the sediment is generally not bioavailable, but labile forms can be redissolved, and particulate bound ionic copper can dissociate back into the water column (U.S. EPA, 1980; Johnston, 1990).

It is extremely difficult to measure the concentrations of various copper species in the environment (EPA, 1980; Ferrari & Ferrario, 1989). Measurements of total copper or dissolved copper do not give an accurate picture of biologically available copper concentrations. Likewise, most toxicity testing of copper uses copper salts that quickly dissociate into ionic form in water and therefore give toxicity information for Cu++ and not for other species of the metal. Measurement of cupric ion activity within a given body of water are valuable, but cannot be used to determine toxic effects on specific organisms. However, Johnston (1990) was able to show changes in the biological responses of fouling communities along a pollution gradient that included labile copper forms in the measurement parameters.

The EPA has set 2.9 mg/L as the maximum level of copper in the water (U.S. EPA, 1980) however the agency does recognize that ambient levels are often substantially higher than this level and that only ionic forms are toxic. New guidance that takes this into account is currently being drafted (U.S. EPA, 1992).

TBT in the environment: The majority of environmental impact studies on biocides from AF paints have focused on TBT. First used as a biocide in AF hull paint in 1961 (Champ & Pugh, 1987), TBT was in widespread use by the mid-seventies and was the most frequently used AF paint biocide in 1987 (Ludgate, 1987). The toxic effects of TBT on non-target (or non-fouling) organisms have been well documented (Champ, 1986). These non-target organisms include both ecologically important species such as the dogwhelk, and commercially important species such as oysters, scallops, and mussels (Bowmer & Farrari, 1989).

TBT is the chemical that is used in AF formulas. It does, however, degrade in the environment into other chemicals. Dibutyltin (DBT) has two butyl groups bound to the tin core, and monobutyltin (MBT) has one butyl group. Generally speaking, the relative toxicity of butyltin increases with the number of butyl groups in the molecule. TBT is about 35 times more toxic than DBT, and DBT is about 750 times more toxic than MBT (Dooley & Kenis, 1987).

Many processes influence the fate of TBT in the environment. Biodegradation, photodegradation, volitization, and adsorption to particulates all play an active role in removing TBT from marine waters (Lee, Valkirs, & Seligman, 1987). Studies have shown that free TBT in the water column degrades stepwise into dibutyltin (DBT) and monubutyltin (MBT) with a half life of about 7.5 days and that the primary process is biodegradation (Lee, Valkirs, & Seligman, 1987; Stang, 1985; Stang & Seligman, 1986). While possibly dependent on suspended sediment concentrations, the amount of total TBT in the water column associated with particulates is typically less than 5% (Valkirs, Seligman, & Lee, 1986).

TBT entering the water in paint chips is less likely to degrade in the water column (Stang, 1985). These chips, along with the dissolved TBT adsorbed to particulates, are deposited in the sediment where they undergo a different degradation process. In the sediment, TBT degrades directly into MBT with a half life of about 162 days. Any DBT that makes its way into the sediment does not degrade at all and acts as a preservation species. This one-step degradation is also primarily from biological processes (Laughlin, 1986; Stang, 1985; Stang & Seligman, 1986).

TBT is particularly a concern at the surface microlayer where TBT concentrations are much higher and put the eggs, larvae, and spores of many marine organisms at greater risk (Cleary & Stebbing, 1987). A particular organism's ability to withstand the toxic effects of TBT seems to depend upon its ability to store the TBT in non-metabolic compartments or to metabolize it into less toxic compounds, i.e., biodegradation (Laughlin, 1986).

TBT AF paints have been banned or heavily restricted for use in many areas around the world because of their high toxicity, potential for bio-accumulation, and apparent persistence in the sediment (Champ & Pugh, 1987). In California, 1988 legislation allows application of TBT AF paints to vessels only if one of the two following criteria is met: 1) the vessel is aluminum (copper AF paint greatly enhances cathodic corrosion on aluminum hulls) or 2) the vessel is over 82 feet long [TBT AF paint is a significant economic benefit on larger vessels because of the longer effective life (California Department of Food and Agriculture, 1988)]. Although the input of TBT into San Diego Bay has presumably decreased since enactment of this legislation, aluminum boats, larger vessels and vessels painted with TBT before the 1988 restrictions, and even dissolution from the sediment reservoir may still be putting some TBT into the water (Waldock, Waite, & Thain, 1987). There have also been unsubstantiated reports from boatowners and maritime businessmen of vessels being painted with TBT in Mexico and of TBT being illegally mixed into other hull paint formulations on the U. S. side of the border.

The EPA has recommended that 10 ng/L be the maximum level of TBT allowable in water (U.S. EPA, 1987).

The Future of AF Paint:

Paint manufacturers are well aware of the environmental concerns surrounding AF paints (De, 1989a). One of the primary options for reducing the adverse environmental impacts from AF paints is to find alternative biocides for use in the paints. Houghton (1984) advanced six criteria for the ideal AF biocide:

1. It should provide long term protection.
2. It should be effective at very low concentrations.
3. It should be innocuous to man, or nearly so.
4. It should be unaffected by inclusion in a suitable media (paint matrix).
5. It should not pollute the environment (impact non-target organisms).
6. It would preferably be biodegradable.

Unfortunately, once a biocide is found that appears to meet these criteria, there is a very lengthy evaluation and approval process a new biocide must undergo before it can be used commercially. Overall, it takes about 10 to 15 years to develop, test, and market a new AF paint (De, 1989a; Fischer, et al., 1984). Steps include full documentation of the properties of the biocide, screening in the laboratory with "panel" or "raft" testing, preliminary ship trials, full scale ship trials, governmental approval, and commercialization. Each of these steps is likely to take years to complete (De, 1989b; Fischer, et al., 1984).

Fouling release hull coatings: In addition to research into new biocides and release mechanisms for AF paints, the paint industry, as mentioned earlier, is working to develop effective "fouling release" coatings. It is widely believed that macrofouling is inhibited on smooth slick surfaces that have not been "conditioned" by microfouling organisms (Fischer et al., 1984). Working in this vein, there has been research into a coating that uses insoluble quaternary ammonium salts grafted onto a vinyl copolymer base. This mechanism has been shown to be effective against microfouling in the laboratory, but it is not yet known if it will have any commercial value (Mellouki, Bianchi, Perichaud, Sauvet, 1989).

Another promising fouling release coating involves fluoropolymers, most notably polytetrafluoroethylene (PTFE). Because of its very low surface energy, no known adhesive can stick to it unless the surface chemistry is altered (De, 1989b). Microfouling can quickly change the surface chemistry of these coatings, but if a toxic agent that targets microfouling could be combined with these slick surfaces, they might afford good long term AF capability (Fischer et al., 1984). PTFE coatings have provided good protection from fouling in field tests lasting 14 and 38 months (Bultman, Griffith, Field, 1984; De, 1989b). Most of the fouling could be removed with light scrubbing, although barnacles still present a problem. In addition to PTFE, fluorinated epoxies and derived polyurethanes also show promise (De, 1989b).

There is another fouling release coating being researched by the U.S. Navy that incorporates cayenne pepper oil into an epoxy based paint. This coating is showing great promise and is currently being tested in Charleston, South Carolina (Hunt for Red, 1993).

Environmental Pressures on San Diego Bay from AF Biocides:

Historically, wastes from shipyards, boatyards, and other repair facilities were dumped or washed directly into the Bay (Barry, 1972; Coe & Michael, 1985). Over the last 20 years, environmental legislation has essentially put an end to these practices, but large sinks of sand blast material and other paint-containing waste are still present in the sediments of the Bay (Stang, 1985; Stang & Seligman, 1986). It is not presently known what effects these sinks may have on water quality (Ferrari & Ferrario, 1989). The other main source of AF biocides to San Diego Bay is the leaching from, and possibly the abrasion of, vessel hulls painted with AF paint (Johnston, 1990; Stang, 1985; Stang & Seligman, 1986). There is very strong evidence that the elevated concentrations of AF biocides in the waters of San Diego Bay are directly related to the presence of large numbers of pleasure craft in the Bay.

Numerous studies have shown that concentrations of AF biocides are highest near marinas and small yacht basins (Grovhoug, Seligman, Vafa, & Fransham, 1986; Stang & Seligman, 1986; Valkirs et al., 1986; Waldock et al., 1987). In the Johnston (1990) study, a continuously increasing gradient of AF biocides was detected moving from the relatively well flushed area at the Naval Ocean Systems Center pier on Point Loma into the poorly flushed Shelter Island yacht harbor less than 2 miles away. Levels of copper were four times as high, TBT nine times, DBT ten times, and MBT four times as high in the yacht basin. The fouling communities in the area of lowest biocide concentration had greater species richness and were dominated by the bryozoan Bogula spp. As the concentrations of biocides increased, the number and diversity of species declined dramatically and the polychaetes H. pacificus and Spirobis spp. overwhelmingly dominated the communities. It is interesting to note that as the concentrations of biocides increased, so did the biomass of the fouling community, as did the dominance of one of the most difficult to remove of fouling organisms, the tube-building polychaetes, although this relationship proved to be non-linear at extremely high concentrations (Johnston, 1990; Fischer, et al., 1984).

The mean TBT concentration in the waters of San Diego Bay was 44 ng/L in 1988 (California Department of fish and Game, 1991); no analogous data for copper was found. Current levels of TBT in San Diego Bay are 5-20 ng/L in the yacht harbors and 1-3 ng/L in the open bay; copper levels are 10-20 mg/L in the yacht harbors and 1-3 mg/L in the open bay (Valkirs, 1993).

Another impact of AF biocides on San Diego Bay is evidenced by the elevated levels of copper and TBT found in the tissues of organisms living in the Bay. In 1974, the mean copper level in digestive glands of M. edulis positioned near the Shelter Island yacht basin was 73 ppm, or about 20 times higher than levels found in mussels positioned in coastal waters (Young, Alexander, and McDermott-Ehrlich, 1979). In 1988, the mean concentrations of TBT and MBT in the tissues of M. edulis positioned throughout San Diego Bay were 856 ppb and 508 ppb respectively; no TBT or MBT was detected in control mussels (California Department of Fish and Game, 1991).

Underwater Hull Cleaning:

UWHC is the practice of wiping, rubbing, scrubbing, or scraping fouling organisms from the submerged surfaces of a vessel's hull while it remains in the water. Information on UWHC in literature is generally scarce, and what there is seems to be limited to the cleaning of large vessel hulls. In San Diego Bay, virtually all UWHC is performed on small pleasure craft. The techniques and tools used in UWHC seem to vary a great deal, but generally fall into two broad categories: power scrubbing for large vessels and hand cleaning for small vessels.

With the possible exception of U.S. Navy vessels, hull cleaning of large seagoing vessels is very rarely done in San Diego Bay. Usually performed by professional diving crews, large scale UWHC operations are not really comparable to the type of cleaning most commonly done in the Bay. Large ships are not cleaned as often as small boats, and consequently tend to accumulate much more fouling growth. Also, as was previously mentioned, larger ships tend to have more hard shell and algal growth than smaller craft.

For these and other reasons, large rotary brush power scrubbers, often resembling over-sized floor buffers, are used to remove fouling from these ships (Preiser & Laster, 1981).

It is known that these large power scrubbers tend to remove substantial amounts of paint along with the fouling growth, particularly over seams and edges or when poor technique is used (Prieser and Laster, 1981). In a study on the effects of power scrubbing on water quality, Cross (1974) reported large quantities of suspended solids consisting of paint chips, fouling organisms, and combinations resulting from power scrubbing operations on large vessels. He concluded, however, that since all visible solids settled rapidly, there was no threat to water quality from these operations. Impacts to sediments were not considered (Cross, 1974).

Much less is known about hand cleaning of small vessels. In San Diego Bay it is believed to be performed by professional hull cleaning services, nonprofessional "weekend" hull cleaners, and individual boatowners. Information about tools, techniques, and schedules varies widely and is poorly documented. Few people outside the boating community are aware of the practice at all, and many within the community are not knowledgeable as to specific tools and techniques. This type of information is obtainable from hull cleaning services, but as of this writing, there are no industry-wide standards or guidelines, other than those offered by a small coalition of divers known as Concerned Divers for Prevention of Harbor Pollution. (These standards are reproduced in Table 1.)

In July of 1991, the California Regional Water Quality Control Board, Santa Ana Region, (CRWQCB-SAR), completed a preliminary study on the release of AF chemicals during hand scrubbing operations (CRWQCB-SAR, 1991). The results of that study showed a significant release of copper and zinc during cleaning. Because this study was limited to a single vessel receiving its first cleaning after fresh bottom paint was applied twelve months earlier, it could be argued that subsequent cleanings would release substantially less contaminants.

Additional methods of dealing with fouling are described briefly in the following section:

Table 1.

Standards of Practice Proposed by
Concerned Divers for Prevention of Harbor Pollution

Source: Bear (1989)

1. Suspend the in-water hull cleaning of vessels with self-polishing or soft sloughing paint.
2. Refrain from hull cleaning for a period of 90 days from new application of bottom coatings.
3. Ninety days after new hull paint is applied, the hull should be cleaned with a "carpet" sponge, or other soft material; however, as the paint becomes less retardant to new growth it may become necessary to use more effective pads to clean the hull. Stainless steel brushes and pads should only be used on nonpainted metal areas.
4. Rotary brush machine cleaning pads should be limited to use of soft nylon or comparable material.
5. Sanding or stripping of hull paint, whether by hand or with a mechanical rotary brush system, should be eliminated.
6. Zincs should be properly disposed of and not left in the water when replaced.

Velocity control: The force of water moving past the hull of a ship significantly reduces the settling of many fouling organisms, and at greater velocities some fouling organisms can be removed from the hull. This method is effective against soft growth on vessels capable of relatively high speeds (Fischer, et al., 1984).

Osmotic control: Most marine fouling organisms will not survive exposure to a hypotonic solution such as fresh water. One of the earliest methods of fouling control involved sailing up a river for a few miles. This method is effective if there is a navigable fresh water source available, but even though it will destroy the fouling organisms, any hard shells will remain and will have to be removed by other means (Fischer, et al., 1984).

Explosive removal: In the early 1970s, a Seattle-based company was marketing a mesh of class-C explosive shock cord that could be positioned around a vessel's hull and detonated. This method was apparently very effective at removing fouling, but damage to sensitive equipment (as well as possible environmental impacts) made it less than cost effective. It was used sporadically for several years after its introduction, but is no longer used for fouling control (Fischer, et al., 1984).

Temperature control: High temperatures can be used effectively against fouling organisms which are generally very sensitive to extreme temperatures. However, the high cost of energy makes large scale application of this method impractical at present (Fischer, et al., 1984).

Light frequency controls: Ultraviolet light is effective at both preventing and removing fouling, but again, energy costs prevent this from being cost effective. Other frequencies also elicit responses from fouling organisms and research is being conducted with the hope of creating a hostile environment for fouling growth and development using various light wave lengths and intensities. In addition, the Navy has been looking at lasers as a means of removing fouling from vessels (Fischer, et al., 1984).

Electric currents and electromagnetic fields: While possibly effective, the high electrical conductivity of sea water makes electricity extremely inefficient. Magnetic fields appear to adversely affect membrane permeability in many organisms, but to date no studies have been made into the possible application of magnetic fields to fouling control (Fischer, et al., 1984).

Ultrasonic control: Devices utilizing various ultrasonic sound frequencies have met with limited success in preventing fouling, but problems with reliability and maintainability of the associated electronics will have to be overcome before this method will be of any practical use (Fischer, et al., 1984).

METHODS:

The underwater hull cleaning survey:

Apart from the 1990 Santa Ana study and the 1988 Nichols study, no information concerning the type of UWHC taking place in San Diego Bay was found. Information from ex-UWHC divers, contractors, government agencies, environmental groups, and area scientists was obtained by various routes. Finally, attendance at meetings of marine businessmen, boat owner groups, marina managers, and regulatory agencies also provided background material.

The survey instruments were modeled somewhat after the one used by Nichols (1988), and developed by RWQCB staff with input from UWHC divers and other interested parties. The surveys were intended to obtain as much information as possible while remaining simple and brief. The format of the surveys was intended to minimize confusion and ambiguity while assuring that no answers would compromise anonymity.

Survey I - Hull Cleaning Companies:

Survey I was designed to obtain information about UWHC directly from the hull cleaners. A list of UWHC services was compiled from listings in the yellow pages and trade journals, advertisements on bulletin boards located around the Bay, and from personal referrals. A total of 35 UWHC services were identified in this manner. It was decided that only owners or diving supervisors of the services would be interviewed, although in many cases the services were one-man operations.

Initial contact with potential hull cleaning companies was made by telephone. With most of the small operations, the only option was to leave taped messages on answering machines. Several attempts were made to contact services that did not respond initially. Eight of the 35 hull cleaners agreed to be interviewed in person, one was interviewed over the phone, and of 14 surveys sent out by mail, seven were returned completed. These 16 completed surveys accounted for the activities of 41 full time divers.

Participants were interviewed and asked the questions as they appeared on the survey form and any clarifications, qualifications, or comments were noted. All interviews of hull cleaners were conducted by the same researcher and every effort was made to assure participants that their responses would remain anonymous.

Survey II - Marine Companies:

Survey II was designed to obtain information from marine businessmen whose operations did not include UWHC. A list of marine businesses was compiled from phone book listings and advertisements in local boating publications. The list included shipyards, boatyards, marinas, repair contractors, riggers, sail makers, supply stores, and other types of businesses. It was decided that repair facilities and marinas would make up the majority of the sample because of their familiarity with UWHC practices. The list was further reduced by the decision to not allow the concentrations of marine businesses around Shelter Island and Harbor Island influence results by over-representing a single area of the Bay. In this manner, a list of 32 marine businesses was generated.

All 32 of these businesses were contacted by phone. Twenty-two agreed to personal interviews at their place of business, and one requested to be interviewed over the phone. Again, participants were assured that their responses would be kept confidential and all interviews were conducted by a single researcher. Questions were asked and responses were recorded in a consistent manner. As with Survey I, all qualifications and comments were recorded on the backs of the surveys.

The final sample of 23 marine businesses included three shipyards (two in the mid-Bay area and one in the South Bay), eight boatyards (six near Shelter Island and two in the South Bay), and seven marinas (three near Harbor Island, two on Coronado, one in the South Bay, and one on Shelter Island). The sample also included two vessel repair contractors, a paint manufacturer, a rigging contractor, and a custom metal fabricator.

Survey III - U.S. Navy:

Survey III was designed to obtain information concerning the UWHC practices of the U.S. Navy. The survey was sent to the Naval Sea Systems

Command in Washington, D.C., via the proper channels. A request was also sent asking for information from a 1980 Navy study on UWHC.

<u>Survey IV - Vessel Owners</u>:

Survey IV was designed for individual boatowners. The format of the questionnaire is essentially the same as that for Surveys I and II, but it was determined that completing the survey by interview would be impractical. It was decided that the survey would be distributed to boatowners by various means, and collected through the mail or through arrangements with marina managers.

The initial distribution techniques used were to leave surveys in marina offices and distribute them at meetings of boating groups. Arrangements were made so that participants could leave completed surveys with their marina managers and they could be picked up later. A cover letter was used to explain the purpose of the survey and assure anonymity. Over 300 surveys were distributed in this manner and 30 were returned.

A second distribution method used survey packets which included a cover letter, the survey, and a pre-addressed stamped envelope for mailing the survey. These packets were distributed by hand to boatowners who were on the docks or on boats at marinas around San Diego Bay. Distribution took place at varying times of day and on weekends as well as weekdays. All contact was done by a single researcher who often verbally explained the purpose of the survey to boat owners and answered any questions they had. A few of these packets were left at marina offices and shops as well. Of the 200 surveys distributed in this manner, 41 were returned completed, to give a total of 71 participants in Survey IV.

Other distribution methods that were considered included presenting the questionnaire in a widely read local boating publication. This was rejected due to prohibitive costs. Mass mailing of surveys to boatowners on a list generated from boat registrations was another option. This was rejected out of concern for creating a perception of invading the boater's privacy. These alternative methods may have yielded substantially more participants and should be considered if a similar study is conducted in the future.

Data from all surveys was entered into the SSPS-X version 3.1 statistical analysis program. All data sets were rechecked manually for accuracy.

RESULTS:

Survey I - Hull Cleaning Companies:

Data from Survey I represents 16 (46%) out of the 35 hull cleaning companies contacted numbering 41 divers. Descriptive data from these companies is presented in Tables 2 and 3. Fourteen of these 41 divers worked for six companies that possessed diving permits issued by the San Diego Port Authority (these permits are currently not required for maintenance operations in marinas in San Diego Bay). All companies had what they considered regular clients who had their vessels routinely cleaned on some sort of schedule. The total number of regular clients from all 16 companies was 3428, or about 34% of the estimated total number of boats on the Bay. In addition to these regular clients, all companies reported cleaning some vessels on a one-time or "odd" basis. For the 1989 calendar year, the total number of "odd" cleanings reported by all 16 companies was 913, or about 9% of the boats on the Bay.

The data shows that 3225, or about 94% of the reported 3428 regular clients, have their vessels cleaned on a 30-day schedule (two of the larger companies indicated that they go to a 21-day cycle in summer months when fouling growth is at its peak, and a 45-day cycle in winter when growth is minimal), 135 of the regular clients' vessels are on a 60-day schedule, 22 are cleaned every six months and four go longer than six months between cleanings.

All of the vessels represented in Survey I had fiberglass hulls. Two companies indicated that they would not clean hulls made of other materials.

All 16 companies indicated that they could recognize an ablative paint surface while working in the water. The owner of one of the largest companies commented that his company will not clean hulls that are painted with ablative paint. Six companies indicated that ablative paints were the most difficult to clean without removing paint with the fouling organisms. Twelve indicated that contact leaching paints in general, and one local brand in particular, were easiest to clean. (The 1988 Nichols study attributed this brand loyalty to marketing and availability of technical assistance rather than objective comparisons of different paints.)

Table 2. Descriptive data for companies represented in Survey I. Number of employees, years in business and customers.

Company	Number of Employees*	Years in Business	Regular Customers	"Odd" Customers
1	0	8	100	50
2	0	20	84	100
3	2	5	90	24
4	3	2	250	40
5	5	20	450	50
6	4	6	500	80
7	0	6	150	25
8	0	1	12	30
9	6	6	600	100
10	0	14	150	25
11	1	10	350	20
12	0	1	105	24
13	1	1	62	15
14	0	8	100	30
15	0	1	125	100
16	3	5	300	200
Total	25	---	3428	913
Range	0-6	1-20	12-600	15-200
Mean	1.5	7.1	214	57

* Not including self

Table 3. Descriptive data for companies represented in Survey I. Vessel size and cleaning schedules.

Company	Average Vessel Size (ft.)	Vessels Cleaned Per Week	Cleaning Time Per Week (hrs.)	Calculated Time Per Vessel (min.)
1	35	30	15	30
2	30	18	10	33
3	32	20	28	84
4	32	65	45	41
5	40	125	70	34
6	40	125	62	30
7	36	35	17	29
8	30	3	2	40
9	40	150	200	80
10	30	40	20	30
11	35	80	60	45
12	32	15	10	40
13	30	15	7	28
14	35	25	20	48
15	33	30	20	40
16	30	75	55	38
Range	30-40	3-150	2-200	28-80
Mean	33.8	53	40	45*

* Calculated from mean hours cleaning per week by mean numbers of vessels cleaned.

All 16 companies who responded were aware of the standards of practice proposed by a local UWHC business association and twelve agreed with these standards completely. All companies indicated that they always tried to clean hulls without removing any paint. One indicated that this was difficult to accomplish. Only one company indicated awareness of any devices for capturing and storing waste products while cleaning hulls Fifteen companies felt that most UWHC divers were conscientious and did all they could to avoid polluting the water.

The survey asked companies if they ever performed any kind of repair work on submerged parts of vessels. Six indicated that they did, although they all attached a qualifier such as "emergencies only" to their answers. Nine denied performing any work other than cleaning. It was later learned during a conversation with the owner of a large company that inspecting and replacing sacrificial zincs, which are small pieces of zinc placed on the hull to help prevent cathodic corrosion, is a routine part of hull cleaning and not considered a "repair."

Fourteen companies indicated that some clients request special hull cleaning prior to hauling the vessel out of the water. All denied that the purpose of this cleaning was to remove old paint, but one did state that these clients wanted him to remove deeply imbedded "black algae" which he must remove with more abrasive tools. All others denied any special tools or procedures were used on these cleanings prior to hauling the vessel out of the water.

All 16 companies indicated that they do make recommendations to their clients regarding when to repaint their hulls. When asked how long a boat can go between paintings with regular cleaning, companies' responses ranged from 18 to 36 months with a mean of 24.7 months.

<u>Damage to environment</u>: When asked if they believed UWHC was damaging to the environment, 13 companies answered no, two answered yes, and one did not respond. Both of the companies who answered yes had qualifiers attached to their answers. One believed that damage is caused by hull cleaners who are not concerned with the environment (and in his response to a previous question, this same hull cleaner indicated that he felt most divers were not concerned). The other company who believed UWHC was damaging felt that the large power scrubbing operations for ships were the cause of the damage and that hand cleaning of small vessels was safe for the environment.

<u>Number of divers</u>: The companies were asked to estimate how many UWHC divers were operating in San Diego Bay. Answered ranged from 18 to 300, with a mean of 86.5.

<u>Estimates of cleaning practices</u>: Hull cleaning companies were asked to estimate what percentage of vessel owners bay-wide subscribe to a UWHC service. Answers ranged from 40% to 90%, with a mean of 71.8%. Estimates of the percentage who clean their own hulls ranged from 1% to 30%, with a mean of 7.4%. Estimates of what percentage of vessels in San Diego Bay never have their hulls cleaned in the water ranged from 2% to 48%, with a mean of 17.9%.

<u>Survey II - Marine Companies</u>:

<u>Repairs/painting</u>: Fourteen of the 23 marine companies that participated in the survey indicated that they do some type of vessel repair. Together, these 14 companies reported doing 10,875 discreet repairs in 1989. They reported a range of from 30 to 3000 repairs, and only one reported doing any underwater repairs. All 14 deny attempting to remove any fouling organisms or old paint while vessels are in the water. Ten of these companies reported that they paint vessels. The total number of vessels painted by these companies in 1989 was reported to be 5006, with a range of from 6 to 2000 and a mean of 500 vessels painted.

The broad range in the number of vessels repaired or painted is explained by the types of companies represented. The three shipyards which service ships 200 feet or more in length account for 65 of the vessel repairs and 56 of the vessel paintings. The eight boatyards which service smaller vessels account for 9080 of the reported repairs and 4950 of the paintings. The two vessel repair contractors reported doing 1500 repairs and no painting.

<u>TBT vs. copper</u>: Participants were asked to estimate what percentage of their paint jobs used TBT vs. copper based AF paints. One shipyard reported that they use only TBT AF paint. The only other shipyard that responded to the question indicated that 6% of their vessel paintings were done with TBT AF paint. All seven boatyard representatives who chose to respond to the question indicated that less than 2% of their clients' boats were painted with TBT based AF paint.

<u>Haul-out cleaning</u>: Vessels requiring major repairs or hull painting must be lifted completely out of the water at the facility performing the service. Companies were asked if they removed fouling organisms from vessels prior

to hauling them out of the water. It was determined that fouling organisms are normally removed after the vessel is hauled out of the water. Comments received from the survey and subsequent conversations with individuals outlined the following procedures. All companies indicated that fouling was removed on shore by hydroblasting or steam cleaning and disposed of as solid waste from their facility and not discharged into the Bay.

UWHC at marinas, docks, and moorings: Companies in Survey II were asked if they allow boat owners to dock or rent slips at their facilities. The 13 participants who answered yes included the seven marinas, one shipyard, and four boatyards. All seven marinas and one of the boatyards allow UWHC at their facilities.

Damage to environment: When asked if they believed UWHC was damaging to the marine environment, twelve companies indicated that they believed it was damaging, eight indicated that they did not, and three did not have a clear opinion.

Number of UWHC divers: Companies in Survey II were also asked to estimate how many UWHC divers were operating in San Diego Bay. Their estimates ranged from 17 to 2000 with a mean of about 210 which is substantially higher than the estimates given by hull cleaning companies. When asked to estimate the percentage of boatowners who subscribe to a service, estimates ranged from 1% to 90% with a mean of 60.8%. Estimates of what percentage of boatowners maintain their own hulls ranged from 0% to 50% with a mean of 10.1%. Estimates of what percentage of boatowners have no hull maintenance ranged from 1% to 75% with a mean of 23.2%.

Survey III - U.S. Navy:

It is known that the Navy does practice UWHC, but the techniques used and to what extent it is performed in San Diego Bay was not available for this study. Repeated attempts to acquire a 1980 report on the UWHC practices of the Navy met with little success. The specially designed questionnaire that was sent to the Navy via proper channels was never returned, and repeated inquiries about it's status were not answered.

Survey IV - Vessel Owners:

Results from Survey IV represent the responses of 71 boatowners who keep their vessels in San Diego Bay. Table 3 gives descriptive data of those vessels.

Hull cleaning frequency: Table 4 shows the hull cleaning schedules reported by vessel owners. The range of reported cleaning frequency was from 18 days to once a year. Almost two-thirds (64.7%) of the respondents reported being on a 30-day or less schedule.

Painting frequency: Table 5 shows the painting schedules reported by vessel owners. The range of reported painting frequency was from once a year to more than three years. A high percentage (53.5%) of the vessels were painted at least every two years.

Table 6 indicates that copper is the most frequent type of paint used on vessel hulls in San Diego Bay. Almost two-thirds (62.5%) of the vessels were coated with a copper based paint. This represents 44 out of the 71 vessels included in the survey and 28 of them are on a two year cycle.

UWHC practices: The survey asked boatowners how they have their vessels cleaned. Fifty-two indicated that they subscribe to a professional hull cleaning service, ten indicated that they do their own cleaning, and six indicated that they subscribe to a service as well as cleaning the hulls themselves. One boatowner indicated "other," and two did not answer the question. Sixty-four of the boatowners reported that their hulls were hand scrubbed, only one reported the use of a power scrubber. Three did not know what method was used on their vessel and three did not answer. Fifty-two indicated that the hull cleaning technique used on their boat was important to them, while fifteen indicated that they did not care, and four boatowners did not answer the question.

Damage to environment: The responses of participating boatowners as a group indicates that the majority do not believe UWHC is damaging to the marine environment. Fifty-seven felt that UWHC was not damaging while seven felt that it was. Seven participants did not respond to this question.

Number of hull cleaners: Boatowner estimates on the number of UWHC divers operating in San Diego Bay ranged from ten to six hundred with a mean of 95. The estimates for what percentage of boatowners subscribe to cleaning service ranged from 5% to 95% with a mean response of 61%.

Estimates for the number of boatowners who clean their own hulls ranged from 1% to 60% with a mean of 16%. Estimates for the percentage of boatowners who do not clean their hulls at all ranged from 10% to 85% with a mean estimate of 18%.

Table 4.

Descriptive Data for Vessels
Represented in Survey III

Type of Vessel

Power	Sail	Total
27	44	71

Primary Use of Vessel

Recreation	Commercial	No Response	Total
66	3	2	71

Vessel Length (feet)

20-30	31-45	>45	No Response	Total
18	42	10	1	71

Hull Material

Fiber-glass	Wood	Fiberglass and Wood	Aluminum	Steel	Other	Total
53	10	2	2	3	1	71

Type of Hull Paint Used

TBT	Copper	Non-Toxic	No Response	Total
18	31	9	13	71

Table 5.

Cleaning Schedules Reported by Vessel Owners

Cleaning Interval	Number	Valid %	Cum. %
Less than 30 days	12	17.6	17.6
30 days	32	47.1	64.7
31 - 59 days	8	11.8	76.5
60 days	8	11.8	88.2
More than 60 days	8	11.8	100.0
(Did not respond)	3	___	___
TOTALS	**71**		

Table 6.

Painting Frequency Reported by Vessel Owners

	Number	Percent
Every year	9	12.7
Every two years	38	53.5
Every three years	20	28.2
Longer than three years	1	1.4
No response	3	4.2
TOTALS	71	100

Table 7.

Painting Frequency by Type of Paint

(Values are percentages)

Painting Frequency (Years)	Type of Paint Used TBT	Copper	Total
1	8	8	16
2	12.5	40	52.5
3+	17	14.5	31.5
TOTAL	37.5	62.5	100

Between Group Comparisons:

The five questions concerning opinions on environmental damage from UWHC, the number of UWHC divers operating in the Bay, and the percentages of boatowners who have their hulls cleaned, self clean, or do not clean their hulls were presented in the same manner on all three surveys. This made it possible to compare the responses of the groups to these five questions.

Environmental damage: Table 7 shows the responses of participants to the question, "Do you feel UWHC is damaging to the marine environment?" by group (responses from Survey II are further broken down by type of business).

Number of hull cleaners: A working estimate for the number of hull cleaners operating in San Diego Bay can be obtained by multiplying the number of known hull cleaning companies operating in the Bay (35) by the mean number of employees per company (2.5) which yields 87.5. This would indicate that the survey population of 41 divers represents about 45% of the total. The mean estimated number of divers from Survey I was 86.5, which is compatible with the working estimate of 87.5. Estimates from Surveys II and IV yielded mean estimates of 209 and 95 respectively.

Who performs UWHC: Table 8 illustrates the relationship between survey estimates by the three groups, the working estimate calculated from information in Survey I, and actual numbers reported by vessel owners in Survey IV for the question of who performs UWHC.

For instance, if 45% of the hull cleaners in the Bay have 3428 regular clients, then the total number of vessels being cleaned on a regular basis by the estimated 87.5 hull cleaners would be 7617, or 76.2% of the estimated total of 10,000 vessels in the Bay. The mean estimate for this value was 71.8% from Survey I, 60.7% from Survey II, and 60.9% from Survey III. Most interesting is that 75.4% of the vessel owners participating in Survey IV report that they subscribe to a service. This value is remarkably close to the calculated estimate of 76.2%. This same calculation can be performed with the 913 "odd" cleanings done by the 41 divers in the survey, resulting in a value of 2028, or about 20.3%. It is likely that these "odd" cleanings are for vessels normally maintained by the owner. The mean estimate for this parameter was 7.4% as given by participants in Survey I, to 1% from Survey II, and 15.9% from Survey IV.

Table 8.

Intra-Survey Responses to
"Do you feel underwater hull cleaning
is damaging to the environment?"

Group	Yes (%)	No (%)	No Resp. (%)
Survey I Hull Cleaners	2 (12)	13 (82)	1 (6)
Survey II Marine Businessman	12 (52)	8 (35)	3 (13)
By Type of Business:			
Shipyards	2 (66)	0 (0)	1 (33)
Boatyards	6 (75)	2 (25)	0 (0)
Contractors	1 (50)	1 (50)	0 (0)
Marinas	2 (28)	3 (44)	2 (28)
Other	1 (33)	2 (66)	0 (0)
Survey IV Vessel	7 (10)	57 (80)	7 (10)
TOTAL	21 (19)	78 (71)	11 (10)

Boatowners' responses from Survey IV showed that 23.2% of the participants either clean their own hulls or supplement self cleaning with occasional professional cleaning, which is comparable with the calculated 20.3%.

DISCUSSION:

This study was designed to provide some insight into the underwater hull cleaning (UWHC) process in San Diego Bay and to assess the impact that the process has on the Bay environment. The extent of the UWHC process is now much better documented. It is also apparent that the Bay environment is impacted by UWHC, but to what degree is beyond the scope of this study. The greatest benefit of the study is that it gives direction for future UWHC investigations.

Survey I - Hull Cleaning Companies:

The best estimate of the number of UWHC divers operating in the Bay is derived from Survey I, as well as information on the techniques and tools used. It is believed that the majority of the participants were honest and straightforward in their responses to the survey, but there are factors which may have influenced the results.

Bias: The intent was to include all UWHC companies in Survey I. This was not achieved, so some bias may have been introduced. Sixteen of the 34 UWHC companies listed in the "yellow pages" participated in the survey. Nineteen companies did not and this could have an effect on the reported results. It is possible that some of these companies chose not to participate in the survey because their UWHC methods were suspect. It is also possible that not all UWHC companies are listed in the "yellow pages". Clearly the effect of the omitting a number of UWHC companies in the survey is unknown.

The results of Survey I may also have been influenced by the economic considerations of UWHC companies. It is possible that some of the UWHC companies answered the survey questions in such a way as to put UWHC in the best possible light. Information obtained from the Surveys II and IV was collected to substantiate the information obtained in Survey I. The relationship between the surveys will be discussed later.

Description of fouling: Question 19 asked respondents to describe the fouling encountered on hulls being cleaned on various schedules; i.e., the

Table 9.

Who Performs UWHC

	Percentage of vessels cleaned....		
	by professional cleaning services	by individual boatowners	only when repainted
Mean Survey I Estimates (UWHC Divers)	71.8	7.4	17.9
Mean Survey II Estimates (Marine Businesses)	60.8	10.1	23.2
Mean Survey IV Estimates (Boatowners)	60.9	15.9	18.2
Working Estimate Calculated from Survey I	76.2	20.3	3.5
Reported by Boatowners in Survey IV	75.4	23.2	1.4

fouling on a vessel being cleaned on a 30-day schedule, on a 60-day schedule, etc. From the answers and comments received, it is clear that hull cleaners felt that this question was ambiguous and all but impossible to answer. As has been mentioned in an earlier section, fouling growth and community composition are determined by a number of variables, not just time. For this reason eleven participants gave vague answers such as "light" or "least" for fouling on a 30-day hull, "medium" or "more" for a 60-day hull, and one used the term "great barrier reef" to describe fouling on a hull that had not been cleaned in over six months. One participant simply answered: "Too many variables."

Four participants actually attempted to describe the fouling at these stages. These descriptions are of little value because of the use of qualifying phrases such as "during coral season," "in summer months," or "with fresh paint." They also contain no species names. Terms such as "algae," "soft growth," "hard growth," "bead coral," "tube coral," "stringiness," and "mossiness" were used to differentiate fouling growth. The "bead coral" might be tunicates or immature tube building polychaetes and "mossiness" might refer to bryozoan growth, etc., so some insight is gained into the fouling community from these four participants' descriptions.

For vessels on 30-day cleaning schedules, fouling might consist of a fully developed primary film, moderate growth of bryozoans, and a few immature polychaetes or tunicates. A vessel on a 60-day cleaning schedule might have a heavier growth of bryozoans, a substantial polychaete population at various stages of growth, and a few tunicates and sponges. On a six-month cleaning schedule, the hull cleaners describe what would most likely be heavy growth of bryozoans and polychaetes, more sponges and tunicates, and a few young barnacles and mussels. For vessels going longer than six months without cleaning, there would be a very heavy growth, dominated by tube building polychaetes and encrusting bryozoans, with more settlement of hard shell organisms such as barnacles and mussels. At this point the entire submerged surface would be completely covered with growth up to several inches thick. While this description is heavily dependent on participant reported observations, they are not inconsistent with descriptions of growth on experimental plates described by Johnston (1990).

Future investigations into the composition of the fouling community must include much more specific questions about the various species present. Common names will have to be verified with identification to genus and species where possible.

Tools used in UWHC operations: Question 20 asked participants to describe what tools were used in UWHC operations on hulls cleaned at various time intervals. Comments and responses suggested that time is one of several variables affecting tool selection. The specific tools used indicated a wide variation between companies, but a few common devices were reported.

Carpet was the most common tool mentioned by respondents. Scraps of carpet were favored for use on "soft growth," and one hull cleaner wrote that the back side of the carpet is effective for removing more stubborn fouling. Nylon pads were the second most commonly used tool. These pads come in various grades of abrasiveness and can be used on nearly all types of fouling growth. Steel wool was mentioned by participants as a hull cleaning tool, but since the grade or coarseness was not known, it cannot be determined what types of fouling it would be used on. Scrapers or putty knives were described by one hull cleaner as "the last resort" for removing hard shell growth.

Overall, respondents indicated that they used the least abrasive tool possible to remove the fouling from any hull. They pointed out that several tools, ranging from carpet to scrapers, might be needed on a single vessel because of varying degrees of fouling. Several hull cleaners denied using steel wool or scrapers except on exposed metal parts such as propellers and shafts. Only one respondent admitted using more abrasive tools for prehaul-out cleanings. All respondents denied ever intentionally removing paint from a vessel in the water.

Benefits of UWHC: Divers have conveyed, in situations separate from the survey interviews as well as through their responses, that they believe UWHC helps to minimize environmental impacts from boating activities. It was mentioned that while cleaning hulls, divers are able to inspect the submerged parts of vessels and inform owners and/or marina managers of potentially polluting problems. Ineffective sacrificial zincs used to control corrosion from electrolysis can be identified or replaced, oil and waste leaks can be seen, as well as structural damage and deteriorated paint. All participants indicated that they advise their clients when the boat needs to be painted, and only one felt that some of his clients painted more often than was necessary.

Nichols (1988) submitted that proper maintenance of hull paints and repainting based on empirical evidence rather than assumption could reduce the input of biocide into the Bay by 33%. This is because of the very high leach rates from fresh hull paints. Reducing painting frequency would also reduce the amount of solid waste from blasting and other painting operations that must be disposed of in landfills. Also, divers have indicated that the clean hulls increase fuel efficiency, thereby reducing pollution from combustion by-products. The divers list several variables that influence this interval including type of paint, cleaning frequency, uses of vessel, smoothness of previous paint application and water conditions such as pH, temperature, and biological activity.

Survey II - Marine Companies:

Survey II provides the means for evaluating the validity of the information provided by the UWHC companies in Survey I. It is assumed that the responses to Survey II were the honest opinions of participants from marine companies, but many factors could have influenced these opinions.

Bias: Survey II was designed to sample a reasonable cross-section of the marine businesses located in close proximity to San Diego Bay. A major problem was the definition of "marine business". It was assumed that boatyards, shipyards, and marinas would have first-hand knowledge of UWHC practices, so it was decided that as many of these businesses would be included in the survey as was possible. There were numerous ancillary marine businesses, but preliminary investigation indicated that these businesses were generally neither knowledgeable nor interested in UWHC. For this reason, only four ancillary marine businesses were selected at random and a fifth was included because it was a major marine paint manufacturer. These five businesses represent a very small sample of all ancillary marine businesses in the San Diego Bay area. On the other hand, marinas, boatyards, and shipyards are proportionally overemphasized.

Additional bias was introduced because businesses located on Shelter Island were randomly removed from the sample to avoid over-representation of a single geographic area (there is a very heavy concentration of marine businesses on Shelter Island).

The above described problems influence the Survey II results, but it is still useful to compare these results with those obtained from UWHC companies in Survey I. Future surveys would be well advised to subdivide this survey into separate categories or to use only the boatyard operations in this survey.

Influence of government regulation: The regulatory environment surrounding the maritime industry is another factor that must be considered when evaluating information from Survey II. The regulations imposed on boatyards and shipyards in the early 1970s were aimed at eliminating discharge of harmful wastes into the aquatic environment and have placed a strain on many of these businesses. Generally, shipyard and boatyard operators feel that UWHC companies discharge the same wastes that they are required to spend large sums of money to contain. Many of the smaller operations claim that they are in danger of being "regulated out of business" and all operations were forced to raise the price of their service to cover the expense of waste treatment technology. Many of the boatyard operators believe that regulation of UWHC would be of economic benefit to them if they could realistically compete with UWHC by offering "haul-out and clean" services. At present, UWHC is far less expensive than haul-out. It is possible that this bias may have inadvertently influenced the answers given by boatyard and shipyard operators. The inclusion of other maritime businesses was to help identify and temper this bias.

Survey III - U.S. Navy:

As was mentioned earlier, repeated attempts to acquire a 1980 report on the UWHC practices of the Navy met with little success. For this report, any attempt to characterize Navy UWHC practices in San Diego Bay would be speculation, and for this reason the characterization of UWHC by the Navy in San Diego Bay is unknown. Future investigations must make an increased effort to obtain the appropriate Navy information on their UWHC practices.

Survey IV - Vessel Owners:

The information from Survey IV provides the best estimate of the extent of UWHC in San Diego Bay. The UWHC companies have information on their clients, but do not have any knowledge about the vessels that they do not service. This information must come from individual boatowners. The small number (71) of boatowners who chose to participate in the survey probably answered questions to the best of their ability, but their knowledge of "the big picture" (i.e., activities not related to their boats) was somewhat limited.

Bias: Participation was strictly voluntary and exposure to the survey was limited. This was readily apparent in that only 71 of the 10,000 boatowners in San Diego Bay participated in the survey. Many of the participants were members of yacht clubs and boating groups and this may have introduced some political bias into the results. Some boatowners may have felt that maintenance costs would increase if there were any regulation of UWHC.

Between Group Comparison:

The comparison of responses of the three groups to identical questions illustrates the difference of opinion concerning UWHC. Many of these differences are likely due to factors which have already been discussed (i.e., shipyard owner's concern about unfair regulation, marine companies worry about unfair competition from UWHC, and fear of increased maintenance costs on the part of boatowners). However, other factors, such as socioeconomic status, education, occupation, and boating experience should not be ruled out as possible reasons for these differences. Should a more comprehensive study be planned in the future, the survey instruments could include questions that address these factors.

Working Estimates:

There has been very little previous work reported in the literature to compare with the results of this survey. The hull cleaning frequency reported by boatowners was consistent with the results of a 1988 Nichols study. No other results from the Nichols study are comparable with the present survey. The only method available for assessing the validity of this survey was to calculate working estimates from the survey results and compare these values with those reported in the various surveys. These estimates are useful for comparing the responses of the three groups and providing a tentative standard of accuracy.

Environmental Impacts from UWHC:

A major concern is whether or not UWHC, when performed properly, has any adverse environmental effect on the Bay. This is a very complex question which cannot be answered definitively with the information obtained in this survey. However, inferences can be made from existing information.

The primary difficulty in answering the question of whether there are any adverse environmental impacts from UWHC is that hulls coated with AF paints are designed to release biocides, the actual cause of these impacts, into the water. This makes it necessary to determine whether UWHC increases the release of biocides beyond that formulated by the paint manufacturer, a task that is greatly complicated by the normal interaction of the paint surface with sea water and fouling organisms.

In San Diego Bay, the most commonly used type of AF paint is the copper-based contact leaching type. It was mentioned earlier that with this type of paint, as the biocide dissolves and moves out of the paint matrix, the leach rate decreases, making it necessary to set the initial leach rate much higher than what would be necessary to control fouling. For this reason, and also to allow the paint to cure completely, freshly painted vessels are not cleaned for a minimum of 90 days in the water after painting. It would be expected that environmental impacts from AF biocides would be greatest during this period, and in fact, there is some evidence that this is the case (Seligman, Grovhoug, and Richter, 1986; Schatzberg, 1987; Anderson & Dalley, 1986; Caprari et al, 1986). This factor alone would make it difficult to quantify biocide release from normally functioning AF paint, but there are further complications.

Various chemicals present in the sea water react with the copper in the AF paint causing relatively insoluble compounds to form on the paint surface (Preiser & Laster, 1981). These compounds, most commonly copper carbonates and oxychlorides, tie up available copper and clog the openings in the paint matrix, thus slowing normal leach rates and decreasing the amount of bioavailable copper.

In addition, a primary film or slime layer forms on any exposed surface submerged in sea water, including one that is actively releasing biocides (Schatzberg, 1987). The organisms, excretions, and byproducts that make up the slime layer act together to clog the channels in the paint matrix and to concentrate the biocide within the organisms that make up the slime layer (Schatzbert, 1987). This also occurs with the macrofouling organisms that settle on the slime layer (Laughlin, 1986).

When a UWHC diver cleans a fouled hull, the fouling organisms are removed and released into the environment along with any biocides they may have concentrated. Also, the copper compounds formed through chemical reactions with sea water on the paint surface are released. If all of these wastes were collected and analyzed, they would most likely contain high levels of biocides, as shown by the California Regional Water Quality Control Board, Santa Ana Region study (1991). This could be interpreted as evidence that UWHC discharges biocides into the environment. How does this discharge compare to the total discharge from normally functioning AF paint over the time period between cleanings without the effects of clogged matrix channels and bioconcentration? Logically, since fouling and bioconcentration slow the leach rate of the paint (Schatzberg, 1987), the waste products would be expected to contain less biocide than would have been leached by unhindered AF paint.

Another source of biocide attributable to UWHC are the paint chips removed from the hull. Power scrubbing is known to remove paint chips along with fouling organisms (Preiser & Laster, 1981; Cross, 1974), and it is possible that chips are also removed with hand scrubbing as well, especially if the fouling includes hard shell growth such as barnacles. According to divers who participated in the survey, the amount of paint that is removed during properly performed UWHC is probably influenced a great deal by age and condition of paint and the technique and smoothness of the paint application. Table 10 lists some important factors in paint application.

Although there have been reports from boatowners and maritime businesses of vessels being completely stripped of paint while still in the water just prior to haul-out, these reports remain unsubstantiated, and the divers in Survey I indicated that the amount of work an operation of this nature would require would make it highly impractical.

It is probable that any paint that is removed during UWHC is incidental, and that divers do their best to avoid removing paint for business reasons as well as environmental concerns. UWHC divers rely on regular customers for the bulk of their business. It would not be good business for them to remove paint or otherwise damage their clients' vessels during the cleaning process.

CONCLUSIONS:

Scope of UWHC in San Diego Bay:

The best estimate obtained from the survey is that about 76% of the estimated 10,000 boats in San Diego Bay have professional hull cleaning service on a regular basis. This service typically includes removal of fouling organisms, inspection of the hull for damage, and replacement of exhausted zincs.

Hull Cleaning Frequency:

This study shows that vessels which are on regular cleaning schedules are most often cleaned every 30 days. The many factors influencing fouling growth (i.e., temperature, pH, hardness, containment concentration, type of hull paint, vessel usage, etc.) make it difficult to set a specific time interval between cleanings. Cleaning intervals should be continuously adjusted based on empirical inspection of a reasonable sample of vessels so that

Table 10.

Proper Bottom Paint Application
Source: Gladstone, 1989

1. New paint and solvents must be compatible with any that remain on the vessel from previous paints. This is because some formulations actually cause others to break down (eg: vinyl will attack epoxy).
2. The surface to which new paint is applied must be super smooth and super clean. Even small particles and rough spots can weaken the bond between the paint and the hull surface.
3. New paint should not be applied on damp or foggy days or when the temperature is below 55 degrees Fahrenheit because moisture in the air and low temperatures interfere with the initial stages of the curing process.
4. If a primer or undercoat is used, it must be compatible with the paint. Using a primer that is the same brand as the paint is recommended.
5. The paint must be applied to a smooth, even thickness in accordance with the manufacturer's specifications.
6. Using a roller for paint application will result in a smoother surface than if a brush is used, and spray application is not recommended.

cleanings are as infrequent as possible without risking damage to hull surfaces or seriously affecting vessel performance.

Who Performs UWHC?

The study shows that about 76% of the hull cleaning done in San Diego Bay is performed by about 87 professional divers with substantial expertise in UWHC operations. In addition, about 22% is performed by boatowners who maintain their own vessels. This leaves only about 2% of UWHC operations to be performed by untrained non-professional hull cleaners who might represent the greatest potential threat to the environment from UWHC.

UWHC Techniques:

UWHC techniques are poorly understood by those who do not perform the task, and are not standardized in any meaningful way by those who do. This survey indicates that very little power scrubbing takes place in San Diego Bay. Most hull cleaning is done by hand scrubbing the hulls with a slightly abrasive material such as carpet scraps or nylon scrub pads. Wire brushes and scrapers are used on exposed metal parts, but these are not painted with AF coatings so there is no increased discharge of biocide from this practice.

UWHC practices should be clearly standardized within the industry to avoid any unnecessary environmental damage. Additionally, boatowners should fully understand the UWHC procedure before agreeing to have their boat serviced. A voluntary standard of practice such as the one described in Table 1, along with a continuing consumer education program, would be helpful in minimizing impacts from poor UWHC technique.

Benefits of UWHC:

Besides the obvious benefits of increased vessel maneuverability and fuel efficiency, there is the potential for increased paint life with a corresponding decrease in total AF chemical discharge. In addition, UWHC provides an opportunity for close inspection of submerged parts of vessels so that damage such as oil leaks can be detected and repaired early.

Possible Impacts of UWHC:

AF paints are designed to release biocides into the environment. Until it can be shown that properly performed UWHC causes AF paints to release biocides at a higher rate than intended by the paint manufacturer, it cannot be concluded that UWHC negatively impacts the environment by discharging AF biocides. Other environmental impacts from UWHC such as paint chipping, metal shavings from propellers and shafts, or discarded zincs and cleaning materials cannot be ruled out by information gathered in this study, but it can be inferred that no responsible diver would intentionally cause these impacts.

AF Paints and Painting Frequency:

Nearly all vessels in San Diego Bay are painted with copper based contact leaching AF paint and are repainted about every two years. Boatowners should carefully assess the need for AF paint on their vessels, and repaint based on need rather than a convenient time schedule.

Factionalism and Public Opinion of UWHC:

The three groups involved in the survey are not in agreement about many aspects of UWHC. This illustrates a pressing need for education in all aspects of fouling and antifouling within the boating industry. A clear understanding of the fouling process, the mechanics of AF paints, and the practice of UWHC by all three groups could benefit the environment by influencing decisions concerning paint formulations, painting frequency, and cleaning frequency.

This survey has established a baseline for UWHC activity in San Diego Bay. Although the numbers are not absolute, it is reported that 76% of all hull cleaning is done by UWHC companies most frequently on a thirty day cycle. The antifouling paint of choice is a copper based contact leaching paint and the preferred painting cycle is every two years.

Environmental impact:

What cannot be reported by this survey is the impact of UWHC on the San Diego Bay environment. The release of biocide into the environment by AF paints is the intended use of these paints on vessel hulls to prevent fouling. This design feature complicates evaluating the environmental impact because the biocide discharge is not a "point source".

What is known is that reputable UWHC companies do not use power scrubbers and this minimizes the additional release of biocide into the environment. In fact when one considers the discharge of petroleum products into the Bay by surface and storm drainage, it is likely the impact of the AF paint discharge is small in comparison.

Any future study of the environmental impact of UWHC on San Diego Bay should include the following:

1. Sampling of fouling materials removed from selected vessels during the UWHC process.
    a. Samples could be collected by scuba divers in "whirl-pac" bags underwater.
    b. Samples could then be analyzed for copper and TBT content.
2. Water samples collected in the vicinity of marinas, vessels moored off shore, and control areas.
    a. Samples could then be analyzed for copper and TBT content.
3. Sediment samples collected in the vicinity of marinas, vessels moored off shore, and control areas.
    a. Again samples could then be analyzed for copper and TBT content.

This sampling program would make it possible to assess the environmental impact that AF paints have on the Bay.

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