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Conceptual Issues in Designing a Policy to Phase Out Metal-Based Antifouling Paints on Recreational Boats

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Abstract

In marine areas throughout the world where recreational boats are densely located, concentrations of copper in the water are being found to be in excess of government standards, due to the hull coatings used on these boats. Copper-based hull coatings are intended to be antifouling in that they retard the growth of algae, barnacles, and coral. Alternatives to commonly used copper hull coatings exist that can eliminate copper contamination associated with recreational boats. A variety of policy options are available to mandate or provide economic incentives to switch to these less harmful alternatives. This paper puts forth a conceptual framework for designing a feasible and low-cost policy to transition to these alternatives.

Keywords: Antifouling paints; Pollution control; Environmental policy; Marine; Copper

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1. Introduction

Toxic antifouling paints are used worldwide to control the growth of organisms such as algae and barnacles on boats' hulls. This growth, known as fouling, creates friction that can decrease a boat's speed, maneuverability, and fuel efficiency. In addition, badly fouled hulls can sometimes act as potential vectors for invasive species. To prevent these adverse effects of fouling, most bottom paints contain a biocide. Copper is currently the most widely used biocide in such paints.

Copper-based antifouling paints are designed to leach copper slowly into the water immediately surrounding a boat's hull, thereby acting as a preventative biocide. Copper also is released into the water when boats with copper-based paint are scrubbed by underwater hull cleaners. Unfortunately, the copper is toxic not only to the potentially fouling organism but also to other organisms in the marine environment at large, particularly at high copper concentrations. In marine areas where recreational boats are densely located, there is concern that the copper pollution problem is posing a major threat to the marine environment. Regulatory agencies in southern California have found that dissolved copper in some boat basins has reached levels that are toxic to some species, and that bottom paints on recreational boats are the primary source of this copper. (California Regional Water Quality Control Board, 2004; US EPA, 2002) Furthermore, sediments that are contaminated with copper are very expensive to dredge from boat basins as they require special handling and disposal methods.

Recreational boat owners have long coated the hulls of their boats with metal-based antifouling paints. The copper-based paints replaced the much more toxic tributyl tin-based paints, which were banned for use on most recreational boats by the U.S.

Environmental Protection Agency in 1987. Copper-based antifouling paints have since become the standard, although they, too, now face regulation in some countries. Along the east coast of Sweden, in the Netherlands, and in Denmark's freshwater areas, they have recently been banned for use on recreational vessels. (Swedish Chemicals Inspectorate, 2004; Danish EPA, 2003; The Netherlands Ministry of Housing, Spatial Planning, and the Environment, 2004; College Toelating Bestrijdingsmiddelen, 2004) In addition, several European countries are monitoring their levels of dissolved copper in boat basins, and antifouling paints applied in the United Kingdom, Sweden, Netherlands, Belgium, Finland, and Austria must be registered under current pesticide laws. (International Coatings Ltd, 2004) These recent regulations toward metal-based paints have, of course, led to increased research and development of nontoxic hull coatings.

Regulatory agencies attempting to phase out toxic antifouling paints face a number of challenges, including the technological availability of nontoxic hull coatings, the cost to boat owners of converting to these alternatives, and the feasibility of implementing and enforcing a program that would induce this conversion. This paper addresses these issues in the context of designing a policy to transition to nontoxic bottom coatings and companion cleaning strategies on recreational boats in San Diego Bay. We discuss the conceptual reasoning supporting our proposed policy, which includes announcing that copper paints will be banned in fifteen years, requiring new boats to be coated with nontoxic coatings, and educating boaters and boatyards as to the cost and properties of newly available nontoxic coatings. Our study demonstrates that such a policy is attractive along many criteria that are important to policymakers, namely feasibility, minimizing costs incurred by recreational boat owners, and minimizing the burden placed on other relevant parties such as boatyards, marinas, and regulatory agencies.

The next section provides background on the policy problem, focusing on regulation toward copper pollution in San Diego Bay. Section III discusses technologically viable alternatives to copper-based antifouling paints. Section IV presents the primary conceptual issues a policymaker faces when designing a policy to induce boaters to switch to these alternatives. Section V proposes recommendations for policy design stemming from the authors' experience analyzing policy options for use in San Diego Bay, and Section VI concludes.

2. Regulatory Background

Dissolved copper concentrations are elevated in many locations throughout San Diego Bay, especially in the southern reaches of the Bay and enclosed yacht basins. (Katz, 1988; VanderWeele, 1996; Valkirs et al., 1994) Numerous studies have indicated that these concentrations exceed the water quality criteria of 3.1 parts per billion (ppb) dissolved copper, which is the federal and state regulatory standard. (USEPA, 2000) As early as 1980, dissolved copper concentrations in the Bay were reported to be as high as 14.2 ppb, and the phytoplankton genera most sensitive to copper toxicity were found to be absent from the innermost waters of the Shelter Island Yacht Basin in northern San Diego Bay. (Kret Lane, 1980) Another study found dissolved copper concentrations of up to 12 ppb in the Shelter Island Yacht Basin. (McPherson and Peters, 1995) In a 1998 US Navy study that evaluated dissolved copper levels throughout the Bay, over half of the samples exceeded the water quality criteria of 3.1 ppb. (Katz, 1988)

Dissolved copper concentrations that exceed state and federal standards of 3.1 ppb are problematic to the marine environment at large because they affect various life stages of marine organisms including mussels, oysters, scallops, sea urchins and crustaceans.[1] When exposed to dissolved copper at concentrations from 3.0 to 10.0 ppb, these species showed reduced or abnormal embryo growth, development, spawning, and survival. (Calabrese et al., 1984; Coglianese and Martin, 1981; Gould et al., 1988; Lee and Xu, 1984; Lussier et al., 1985; MacDonald et al., 1988; Martin et al., 1981; Redpath, 1985; Stromgren and Nielsen, 1991) A number of studies have also found that many of these effects become more severe at dissolved copper levels ranging from 10.0 to 29.0 ppb, and that feeding, respiration, and waste elimination of adult mussels were also affected. (Krishnakumar et al., 1990; Redpath and Davenport, 1988)

Under the California Water Code, the California Regional Water Quality Control Board is responsible for protecting surface waters by regulating the discharge of pollutants into those waters, as required under the federal Clean Water Act (CWA). For any impaired water body, the CWA requires every state to establish Total Maximum Daily Load (TMDL) Programs to attain water quality objectives. Once the TMDL has been implemented and pollutant discharges have been reduced, water quality standards should be achieved.

According to TMDL studies, elevated levels of dissolved copper in San Diego Bay are due in part to copper-based antifouling paints on boats, particularly in areas where recreational boats are densely located. The Shelter Island Yacht Basin harbors over 2,200 recreational boats (according to the San Diego Port District Harbor Police's

[1] Phytoplankton and zooplankton, including bivalve larvae, are the organisms thought to be most sensitive to copper toxicity. See the California Regional Water Quality Control Board's Total Maximum Daily Load for Dissolved Copper in the Shelter Island Yacht Basin (2003) for further discussion.

annual Pleasure Craft Survey), and 99% of the dissolved copper in this basin is thought to come from antifouling paints. (CARWQCB, 2003) Regulators are also concerned about copper pollution in Newport Bay, Santa Barbara's harbor, the harbor at Oceanside, and various other parts of San Diego Bay, and another TMDL study for dissolved copper is currently being conducted for Marina Del Rey.[2]

The high concentrations of copper in these marine areas stems from the technological nature of antifouling paints on boats that are kept there. Pleasure craft commonly spend much time at their slips, where the antifouling paints continuously emit copper that may accumulate in marinas with poor water circulation. This type of copper loading is referred to as "passive leaching," and is thought to be the most significant source of dissolved copper coming from antifouling paints. The contribution of passive leaching to the copper pollution problem in San Diego Bay has been estimated to range from 56% to 95% of copper loading. (PRC Environmental Management, 1997; Schiff et al., 2003) The other major source of copper release is underwater hull cleaning, as the scrubbing of copper-containing paints releases dissolved copper into the surrounding water. The total amount of copper released during cleaning depends on a range of factors, including how frequently the hull is cleaned, the method of cleaning, the type and thickness of paint, and the frequency of painting. Ideally, cleaning is performed regularly so organisms do not have a chance to become firmly attached, but when hulls need to be scrubbed hard to remove fouling, the copper release problem can be exacerbated.[3]

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[2] Dissolved copper levels that are higher than permitted under state laws are not limited to California. Within the U.S., other areas of concern include Chesapeake Bay, Maryland, Port Canaveral and Indian River Lagoon, Florida, and areas of Washington State. See Hall et al. (1988), Sheffield Engineering (1988), Trocine and Trefry (1993), and Stasch and Lynch (1999).

[3] Professional underwater hull cleaners in San Diego are sensitive to the Bay's copper pollution problem, and employ Best Management Practices in attempts of minimizing copper emissions.

Switching to nontoxic hull coatings would reduce copper loading from both passive leaching and underwater hull cleaning.

3. Availability of Nontoxic Coatings

Awareness of and interest in the copper pollution issue has surfaced due in part to the possibility of increased regulation to reduce copper levels. The availability of nontoxic antifouling strategies has increased correspondingly. These strategies generally combine a nontoxic hull coating and a "companion strategy" such as cleaning the hull frequently, storing the boat out of water, or surrounding it with a slip liner. Though many nontoxic hull coatings are currently available, they are new to the market and consumers generally know very little about them. (Carson et al., 2002) However, as the public has become more aware of the toxic effects of copper, and as the copper content of paint has begun to take on a negative connotation among buyers, major paint companies have begun to study biocide-free paints extensively. (Kettlewell, 2000)

Understanding certain technological features of antifouling strategies is necessary for policymakers to understand costs of using nontoxic hull coatings. First, nontoxic coatings do not prevent organisms from attaching to boats' hulls, so they must be cleaned more often than traditional copper-based paints. However, a durable nontoxic coating may last longer than a copper-based paint because its effectiveness at preventing fouling does not depend on the presence of a biocide which leaches out of the paint over time. Costs of purchasing nontoxic coatings, preparing the hull, and applying the coating tend to be higher than for copper-based paints. However, as more paint companies develop and market nontoxic coatings and as boat repair and maintenance companies learn appropriate application procedures and cleaning protocols, the costs of using these paints are likely to fall.

Currently available nontoxic bottom coatings may be silicone-based, epoxy-based, water-based, or polymer-based. Epoxy coatings are currently the most widely used type of nontoxic bottom coating; they tend to be highly durable, require frequent cleaning, and are expected to last for many years. Manufacturers of two nontoxic epoxy-based coatings report that their coatings have lasted from 6 to 12 years on some boats. Though independent testing is still scarce, initial anecdotal evidence supports this claim.[4] In contrast, most San Diego area boat owners reapply copper-based bottom paint every two to three years.

Silicone hull coatings provide another nontoxic alternative to copper-based paints. These paints are sometimes called "fouling release" coatings, because fouling organisms slide off the hull when a boat exceeds a certain speed. Field tests have found that the critical speed for fouling release varies for different silicone coatings and for different organisms, though 20 knots is often cited. (See, for example, Swain, 2000, 2001.) Although many pleasure craft seldom or never operate at this speed, the slippery nature of these coatings also allows for fouling growth to be wiped off easily. San Diego area hull cleaners recommend especially frequent cleaning of silicone coatings, as they believe that later stages of fouling growth can penetrate these coatings and become more firmly established on the hull. Also, because of the slippery nature of silicone, boats with these coatings require special handling at boatyards and can sometime pose a danger to maintenance workers.

[4] One San Diego area sailboat that received an epoxy coating more than seven years ago, and the diving service that cleans it reports it is still in good condition.

In addition to testing that is being conducted by product manufacturers, extensive independent testing of new nontoxic hull coatings is still very much needed. Studies on boats in typical recreational use would provide both regulators and consumers with valuable and applicable data. Factors such as water temperature variations should be considered in different parts of the world and across different seasons. Boat type, frequency of use, cleaning effort and frequency, and coating condition and performance need to be documented for these coatings to be better understood. Over the long term, such studies would provide information that boat owners and boat repair and maintenance operations will need in order to select, recommend, and maintain nontoxic bottom coatings.

The University of California Sea Grant Extension Program in San Diego County has conducted an educational demonstration to provide preliminary information on nontoxic antifouling strategies. The project tracked the performance of three silicone- and epoxy-based coatings on six vessels in San Diego Bay from 2002 to 2003. They established a reporting protocol to obtain data from underwater hull cleaners who documented fouling growth, cleaning tools, diver effort, and coating condition each time the vessels were cleaned. Most notably, the epoxy coatings withstood intensive cleaning and showed promise of extended service life.

4. Transitioning to Nontoxic Paints

4.1 Policy Objectives and Evaluation Criteria

To develop a policy toward copper-based hull paints on recreational boats in San Diego Bay, it was first necessary to specify the policy's objectives and the criteria for evaluating the merits of a specific policy. Following the language of California Senate Bill 315, we considered two complementary policy objectives:

1) Development of a plan that meets the California Regional Water Quality Control Board: San Diego Region's proposed (April 23, 2001) Total Daily Maximum Load (TDML) requirement of a 66% reduction in dissolved copper coming from recreational boats in Shelter Island Yacht Basin.
2) Development of a plan that results in the eventual phase-out of copper-based hull paints on recreational boats in San Diego Bay.

Any phase-out of the use of copper-based hull paints will require that the 66% reduction required by the Regional Board's TDML be met first. The Regional Board's objective of a 66% reduction in current dissolved copper coming from recreational boats can therefore be seen either as an intermediate step toward a final phase-out or as a final policy end point. The conceptual issues pertinent to the consideration of these two objectives will be equivalent, so for simplicity we considered policies that could induce a complete phase-out of copper.[5]

We considered the design of a pollution control policy with respect to three main criteria:

1) Feasibility
2) Cost to recreational boat owners
3) The burden placed on other relevant parties (i.e. boatyards, hull cleaners, marinas, the Port District and the State of California)

After narrowing our analysis to policies that can feasibly be implemented, policies that have lower costs and place lower burdens on other relevant parties were preferred. In

[5] It is beyond the scope of this study to consider the relative desirability of these two objectives.

other words, a policy is considered strictly better than another policy if it is superior to that policy on all three of these dimensions.[6] The remainder of this section discusses the optimal design of a policy for use in San Diego Bay according to these three criteria.

4.2 Feasibility and the Constraint of Boatyard Capacity

As discussed above, antifouling paints are designed such that the copper slowly leaches off of a boat's hull to act as a preventative biocide. Because the toxic element is constantly leaching out of the paint, boaters with copper-based hull paints need to reapply them relatively often, approximately every 2-3 years at San Diego Bay.[7] Each repainting requires a boat to be hauled out of the water and is usually performed at a local boatyard. In addition, because new coats of the paint generally are applied directly on top of the old coats, old paint accumulates and new coats become increasingly difficult to apply. After about 6 repaintings, a boat's hull usually needs to be stripped entirely clean of the old paint in order to begin applying new coats again. Essentially, a clean hull is a new capital asset which depreciates over time, until it is fully depreciated and needs to be "replaced" (*i.e.* stripped) on average every 15 years. Stripping is a very expensive component of a boat's maintenance schedule, generally costing $150 per foot of a boat's length. Figure 1 summarizes average maintenance properties of copper-based antifouling paints and non-toxic epoxy hull coatings.

Nontoxic coatings cannot be applied directly on top of copper-based paints; therefore, a hull with any amount of copper paint accumulation would need to be stripped

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[6] Otherwise, different stakeholders may place different weights on these criteria, and hence judge different policies preferable.

[7] Figures pertinent to maintenance requirements and their costs were obtained by surveying boatyards and boat owners. See Carson et al. (2002).

in order to be converted to a nontoxic coating. In addition to the considerable cost of application, this particular feature of nontoxic coatings makes a very quick paint conversion of an entire population of boats infeasible due to the practical constraint of limited boatyard capacity. Boatyards routinely perform paint jobs and stripping jobs, and in San Diego Bay, boatyards serve a stable population of boats and are operating at close to full capacity. Stripping and repainting a boat takes more time than simply repainting a boat, so an immediate conversion of all 7 000 boats in San Diego Bay would place a demand that currently could not be met by boatyards.

The ability to increase capacity through reorganization of work, hiring additional staff, and obtaining additional equipment is standard in most industries. However, the limited ability to store boats on location, coupled with the need for the paint applied to boats to dry adequately, suggest that very large increases in boatyard capacity are unlikely in this specific case. An additional reason that boatyards are unlikely to purchase new equipment is that, while a policy requiring conversion to nontoxic coatings will create more hull maintenance work in the short term, in the long run the use of nontoxic hull coatings actually implies less hull maintenance work by boatyards. This is because nontoxic coatings generally do not need to be reapplied as often as copper-based paints because their efficacy does not depend on biocide leaching from the coating. Boatyards are therefore faced with a strong incentive against large capital expenditures that would substantially increase long-term hull maintenance capacity.

The minimum time horizon for any policy to phase out copper is therefore determined by the constraint of boatyard capacity. Boatyard capacity constraints prevent immediate conversion of the current fleet of recreational boats on San Diego Bay from copper paints to nontoxic coatings. However, since nontoxic epoxy hull coatings need to be reapplied less often, boatyard capacity is freed over time as boats in the population convert to nontoxic coatings, and this additional capacity can be used for conversions over time. By speaking to boatyards and deriving a simple dynamic model of conversion capacity, Carson et al. (2002) determined that the quickest possible time horizon in which the objective of a 66% reduction in copper discharge could be achieved (after large scale commercial application is viable) is five years. The minimum time horizon necessary to achieve a complete phase-out in San Diego Bay is seven years.

4.3 Costs to Recreational Boat Owners

Once the set of practically feasible policies is determined (*i.e.* policies that allow at least seven years for a phase-out), we can consider ways to design a policy with the other three policy objectives in mind. One of the most important criteria is the cost that recreational boat owners will bear under the new regulation. Any change in the cost of maintaining a boat will generally be borne by the boat owner, and the true cost of any policy can therefore be thought of as the total change in hull maintenance costs. Realizing that no policy can feasibly impose immediate conversion over the population of boats, and that in San Diego a phase-out will need a minimum of seven years, we next ask whether we can lower the costs that boat owners will bear through a well-informed policy design.

An economically rational boat owner should consider the present discounted value of hull maintenance over a boat's lifetime when making hull paint decisions. Even if he or she plans to sell the boat before it is permanently retired, the resale value of a boat in an efficient market will depend on features of the boat such as its current paint type and the ensuing necessary maintenance costs. Therefore, boaters should make cost calculations over the expected remaining service life of a boat. Evidence from surveys of boat owners in San Diego empirically demonstrates that this is indeed true for this population of boaters.[8]

To formally model the boat the boat owner's cost minimization problem, we let $C(t;l,c_f,c_c)=\sum_{i=1}^{E*c_f}\delta(t-i/c_f)*c_c*l$ represent the stream of an individual boat owner's cleaning costs, where c_c is the cost per foot of cleaning a hull each time it must be cleaned, c_f is the number of times per year that it must be cleaned, l_i is the length in feet of individual *i*'s boat, and $\delta(\cdot)$ is the Dirac delta function, with the property that $\int_{-\infty}^{\infty}\delta(x)*f(x)dx=f(0)$.[9] Similarly define $P(t;l,p_f,p_c)=\sum_{i=1}^{E*p_f}\delta(t-i/p_f)*p_c*l$ as the recurring cost of painting te boat and $S(t;l,s_f,s_c)=\sum_{i=1}^{E*s_f}\delta(t-i/s_f)*s_c*l$ as the cost of stripping the boat. An individual cost-minimizing boat owner therefore chooses T, the time to switch from a copper-based paint to a non-toxic hull coating (denoted with superscripts 0 and 1, respectively), to solve:

$$\min_T \int_a^T (C(t;l,c_f^0,c_c^0)+P(t;l,p_f^0,p_c^0)+S(t;l,s_f^0,s_c^0))*e^{-r(t-a)}dt \\ +\int_T^E (C(t;l,c_f^1,c_c^1)+P(t;l,p_f^1,p_c^1)+S(t;l,s_f^1,s_c^1))*e^{-r(t-a)}dt \qquad (1)$$

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[8] The survey of San Diego boaters was conducted by the authors in the summer of 2002, in order to understand how boat owners choose between different hull paint options. The methodology and results of this survey are discussed in Carson, et al. (2002).

[9] The Dirac delta function is used here to represent discrete costs incurred in a continuous time framework. It is sometimes referred to as the "unit impulse function"; essentially, the Dirac delta is the limit of a standard normal distribution as its variance approaches zero. It returns an impulse with a mass of 1 when its argument is 0 and returns 0 for all other arguments. For further discussion, see Bracewell (1999) and Papoulis (1984).

where a represents the age, in years, of her boat today, and E represents the age at which her boat will be retired.

The boat owner's comparison between traditional copper-based hull paints and a nontoxic alternative such as an epoxy hull coating will almost always show that the copper-based hull paint has lower initial costs. The cost advantage becomes even larger if one considers costs over the first couple of years, as it is currently less expensive to paint a boat with traditional copper paint, and the cost of maintenance is lower because a hull painted with traditional copper paint needs to have its hull cleaned less often. However, taking a longer perspective can reverse this conclusion, primarily because a nontoxic epoxy hull coating tends to last considerably longer than a copper-based hull paint. When making cost calculations, this lower frequency of incurring the repainting cost should be balanced against the higher initial painting cost and the higher hull cleaning costs over the course of the life of the nontoxic hull coating.

As discussed, there is an additional cost that is highly significant when comparing costs across paint types: the cost of stripping old accumulated paint. A boat that is always repainted with copper hull paint must be stripped periodically (after roughly 6 repaintings), and the owner of a boat with copper hull paint who wishes to switch to a nontoxic coating must also strip all of the old copper paint from the hull. Stripping costs tend to be much larger than the painting costs (*e.g.* $150 per foot of boat length for stripping old paint and applying new paint versus $30 per foot of boat length for applying traditional copper paint on a 40-foot boat). Thus, a comparison of total lifetime costs depends critically on whether the boat has to incur an additional stripping cost in order to apply the nontoxic hull coating.

There are two situations in which an additional stripping is not required in order to apply a nontoxic coating. The first is when painting the hull of a new boat, since there is no accumulated paint to remove. New boats come with "gel coats" that most often are then coated with a traditional copper-based paint. Alternatively, a nontoxic coating may be applied directly to the gel coat without additional preparation. The other situation in which copper paints and nontoxic coatings face identical stripping costs is when an older boat has an accumulation of old copper paint that must be stripped before new copper paint or a nontoxic coating will correctly adhere. More generally, the closer an existing boat with copper paint is to needing to be stripped, the more favorable the cost comparison between the copper paint and the nontoxic coating will be. In this sense, a new or newly stripped hull can be seen as an asset that depreciates over time, each time it is repainted. A hull that needs stripping can be thought of as a fully depreciated hull. A policymaker's understanding of this intuition is crucial when thinking about the lowest-cost way to design a policy. (This point is discussed at length later in this section.)

Lastly, when thinking about the nature of a boat owner's costs, it is important balance the costs occurring in different time periods with an appropriate discount rate. Different people may view policies with the same costs but occurring in different time periods differently, due to the discount rate they perceive to face with respect to hull maintenance decisions. Survey evidence found that boat owners in San Diego Bay trade off hull maintenance costs over time at a 5% discount rate, on average. (Carson et al., 2002)

Total lifetime maintenance costs for a new 40-foot boat in San Diego Bay are shown in Figure 2.[10] It can be seen clearly in this figure that using copper-based paint is less expensive at the start, but this cost advantage falls as one considers total lifetime cost over longer time horizons. The nontoxic coating becomes the less expensive alternative at a time horizon of 18 years or longer. The other thing to note is that, for time horizons of 5 years or greater, the difference in the total lifetime cost profile of copper paints and nontoxic coatings is fairly small.

Understanding these cost comparisons sheds valuable insight to the design of a policy that attempts to minimize costs to boat owners. As mentioned above, one primary policy implication stems from the fact that, at any given time, there are two types of boats for which an additional costly stripping need not be incurred in order to convert to a nontoxic coating: new boats and boats that need to be stripped before any other paint can be applied. Clearly, a policy should begin by targeting these boats. Coupled with the fact that a policy cannot feasibly impose immediate conversion, a policymaker can lower the cost of the policy by targeting these boaters first.

A crucial point here is as follows: once regulators realize that all boats cannot be ordered at once to convert to nontoxic coatings, due to the constraint of boatyard capacity, they need to consider the ordering of which boats should switch first. If attempting to minimize the cost of the policy, the first boats to convert should be all new boats and all boats in need of a stripping. If the policy were allowed a long enough time horizon, these could be the only boats the policy ever needs to target, and 100% abatement could be achieved once every boat with a copper-painted hull in the population

[10] Baseline cost assumptions are summarized in Figure 1; additionally, boats are assumed to be retired at 30 years of age. All assumptions come from conversations with San Diego boatyards, marinas, and recreational boaters. See Carson et al. (2002) for further discussion.

either needs to be stripped or is permanently retired. To phase out copper in a shorter time horizon, the policymaker should target boats that need to be stripped very soon as the next group of boaters to convert, and so on until enough boats are targeted in each period to achieve 100% abatement in the desired amount of time. To choose the appropriate timeframe in which to achieve the conversion, the policymaker needs to weigh the costs and benefits of allowing a longer time horizon for the phase-out against the benefits of achieving abatement sooner, within the constraint of the minimum feasible time horizon due to boatyard capacity.[11] Essentially, the policy needs to induce the paint conversion of the least-cost group of boaters at any given time, where this group is large enough to achieve the conversion within the chosen time horizon.

Once the best (least cost) group of boaters to convert in each period is identified, policymakers have a menu of policy "instruments" which can be used to achieve the desired conversion. For example, a regulatory agency could subsidize conversion to nontoxic coatings by paying boatyards to offer nontoxic coating application at a lower price. If this price is set to exactly offset the lifetime cost differential between a copper paint and a nontoxic coating for a hull that has just been stripped, then this subsidy will induce these boaters to convert and will effectively target the right group at the right time. (Other groups will not convert because their cost differential is necessarily more favorable to copper paint than a clean, stripped hull, so the subsidy would not be high enough to change their behavior.)

5. Design of a Policy for Use in San Diego Bay

[11] To rigorously address this tradeoff would require the usual economist's weighing of marginal social costs and benefits in order to achieve the socially efficient outcome. The cost efficiency framework adopted here allows us to recognize efficiency gains through means of implementation in a given time horizon.

Perhaps the most revealing aspect of the recent study in San Diego Bay is that no such subsidy (or alternative policy instrument) would be needed to induce the boaters at optimal points to convert to non-toxic hull coatings, as long as the policy's time horizon is a minimum of fifteen years. This result comes from two findings of the surveys conducted by Carson, et al. (2002). The first is that the population of boaters in San Diego is willing to pay a considerable premium for the nontoxic property of coatings; on average, this premium is $800 for the nontoxic *property* alone, holding other properties (cost and frequency of paint application, cleaning, etc.) equal.[12] This willingness-to-pay turns out to be greater than the cost differential between nontoxic coatings and copper paints (which had favored copper) over the remaining lifetime of a boat that is being stripped today. Therefore, once the environmental concern among boaters in San Diego is taken into account, and once boaters are well educated as to the costs and properties of nontoxic coatings, boaters who are stripping their "depreciated" copper-painted hull will choose to apply nontoxic coatings on their own, without any additional economic incentive provided by a policy.

The second survey finding that supports this notion is that announcing a future ban on copper paint would significantly affect the choice of paint type that a boat owner currently makes. This second finding suggests that the resale value of boats would truly reflect the increased cost of using copper paint that a ban would cause and, more specifically, the ban would cause boats with nontoxic-coated hulls to be worth more. Therefore, even boaters with less-than-average concern for the environment will switch, so long as these boaters are well informed.

[12] See Damon and Carson (2004) for a more detailed and technical discussion of these findings.

In light of the vast ease of implementation and low cost of such a policy, a reasonable policy recommendation for use in San Diego Bay is as follows: Announce that copper paints will be banned in fifteen years, require new boats to be coated with nontoxic coatings, and educate boaters and boatyards as to the cost and properties of newly available nontoxic coatings. The cost of this policy will be the cost of the education campaign, and will not require any additional cost to the government agency or the boat owner, as would a subsidy or a tax program.

If policymakers instead wish to achieve a complete phase-out in under fifteen years, they must make use of policy instruments to create economic incentives or mandates in order to induce boaters to switch to nontoxic coatings when they otherwise would not have. They can employ these instruments to reduce the lifetime cost differential of paints for the boaters they wish to target in order to achieve the least-cost time path of conversion, as discussed above. However, shorter desired time horizons will necessarily lead to higher costs, and the costs increase considerably as the horizon approaches the lower-bound of seven years, because boat owners will essentially be forced to retire assets which are not yet depreciated (*i.e.* hulls that would not need to be stripped for many years to come).

6. Conclusion

Copper pollution from antifouling paints is affecting coastal water quality all over the world in areas where there are high concentrations of recreational boats. Regulatory approaches to the problem will continue to evolve as governments become increasingly aware of the copper concentrations in their waters and as viable alternative nontoxic coatings continue to be developed.

Policies used to address the copper pollution problem need to be focused on specific local populations of boat owners and, furthermore, need to selectively target certain boat owners at various points in time in order to minimize the cost of the policy, which boat owners will generally bear. In San Diego Bay, requiring that new boats use only nontoxic coatings and announcing that copper paints will be banned on existing boats in fifteen years would accomplish this objective of a low-cost and administratively feasible phase-out policy. It is our hope that lessons learned while designing such a policy for use in San Diego Bay can be useful to regulators addressing this pollution problem in other marine areas.

References

Bracewell, R., 1999. The Impulse Symbol. Ch. 5 in The Fourier Transform and Its Applications, 3rd ed. New York: McGraw-Hill, 69-97.

Calabrese, A., MacInnes, J.R., Nelson, D.A., Greig, R.A., Yevich, P.P., 1984. Effects of Long-Term Exposure to Silver or Copper on Growth, Bioaccumulation and Histopathology in the Blue Mussel Mytilus edulis. Marine Environmental Research 11, 253-274.

California Regional Water Quality Control Board, San Diego Region, 2004. Total Maximum Daily Load for Dissolved Copper in Shelter Island Yacht Basin, San Diego Bay, Public Review Draft.

Carson, R.T., Damon, M., Johnson, L.T., Miller, J.A., 2002. Transitioning to Non-Metal Antifouling Paints on Marine Recreational Boats in San Diego Bay. Pursuant to Senate Bill 315 passed in 2001; submitted to California Department of Boating and Waterways.

Coglianese, M.P., Martin, M., 1981. Individual and Interactive Effects of Environmental Stress on the Embryonic Development of the Pacific Oyster, Crassostrea gigas. Marine Environmental Research 5, 13-27.

College Toelating Bestrijdingsmiddelen, 2004. Pesticides Database Online. http://www.ctb-wageningen.nl/.

Danish Environmental Protection Agency, Ministry of the Environment, 2003. Statutory Order on Biocidal Antifouling Paint. Document. Available at: http://www.mst.dk/homepage/default.asp?Sub=http://www.mst.dk/rules/.

Gould, E., Thompson, R.J., Buckley, L.J., Rusanowsky, D., Sennefelder, G.R., 1988. Uptake and Effects of Copper and Cadmium on the Gonad of the Scallop Placopecten magellanicus: Concurrent Metal Exposure. Marine Biology 97, 217-223.

Hall, W.S., Bushong, S.J., Hall Jr., L.W., Lenkevich, M.J., Pinkey, A.E., 1988. Monitoring Dissolved Copper Concentrations in Chesapeake Bay. Environmental Monitoring and Assessment 11, 33-42.

International Coatings Ltd. UK and International Paint Inc., 2004. Antifoulings: The Legislative Position by Country. Available Online at http://www.yachtpaint.com/superyacht/sy/pdf/antifouling_legislation.pdf.

Katz, C., 1988. Seawater Polynuclear Aromatic Hydrocarbons and Copper in San Diego Bay. Technical Report 1768, Space and Naval Systems Center (SPAWAR), San Diego, CA.

Kettlewell, J.J., 2000. “Marine Paint Marketers Change the Pitch.” Boating Industry International Online Archives. http://www.boating-industry.com/ January 2000.

Krett Lane, S.M., 1980. Productivity and Diversity of Phytoplankton in Relation to Copper Levels in San Diego Bay. Technical Report 533, Naval Ocean Systems Center.

Krishnakumar, P.K., Asokan, P.K., Pillai, V.K., 1990. Physiological and Cellular Responses to Copper and Mercury in the Green Mussel Perna viridis (Linnaeus). Aquatic Toxicology 18(3),163-173.

Lee, H.H., Xu, C.H., 1984. Effects of Metals on Sea Urchin Development: A Rapid Bioassay. Marine Pollution Bulletin 15, 18-21.

Lussier, S.M., Gentile, J.H., Walker J., 1985. Acute and Chronic Effects of Heavy Metals and Cyanide on Mysidopsis bahia (Crustacea: Mysidacea). Aquatic Toxicology 7, 25-35.

MacDonald, J.M., Shields, .JD., Zimmer-Faust, R.K., 1988. Acute toxicities of eleven metals to early life-history stages of the yellow crab Cancer anthonyi. Marine Biology 98, 201-207.

Martin, M., Osborn, K.E., Billig, P., Glickstein, N., 1981. Toxicities of Ten Metals to Crassostrea gigas and Mytilus edulis Embryos and Cancer magister Larvae. Marine Pollution Bulletin 12, 305.

McPherson, T.N., Peters, G.B., 1995. The Effects of Copper-Based Antifouling Paints on Water Quality in Recreational Boat Marinas in San Diego and Mission Bays. In-Water Hull Cleaning Study, Ambient Concentrations Study and Tidal Influence Study. California Regional Water Quality Control Board, San Diego CA.

Papoulis, A., 1984. Probability, Random Variables, and Stochastic Processes, 2nd ed. New York: McGraw-Hill, 97-98.

PRC Environmental Management, Inc., 1997. Report of Copper Loading to San Diego Bay, California. Prepared for California Regional Water Quality Control Board, San Diego Region and the San Diego Bay Interagency Water Quality Panel.

Redpath, K.J., Davenport, J., 1988. The Effect of Copper, Zinc and Cadmium on the Pumping Rate of Mytilus edulis L. Aquatic Toxicology 13, 217-226.

Redpath, K.J., 1985. Growth Inhibition and Recovery in Mussels (Mytilus edulis) Exposed to Low Copper Concentrations. Journal of the Marine Biological Association of the United Kingdom 65(2), 421-31.

Schiff, K., Diehl, D., Valkirs, A., 2003. Copper Emissions from Antifouling Paint on Recreational Vessels. SCCWRP Technical Report #405. Southern California Coastal Water Research Project. Westminster, CA.

Sheffield Engineering, 1988. Sediment Analysis of Canaveral Harbor. Report to Canaveral Port Authority.

Stasch, P., Lynch, D., 1999. Ship Shape. Single Industry Campaign: Summary Report, Publication No. 99-16. Washington State Department of Ecology, Water Quality Program.

Stromgren, T., Nielsen, M.V., 1991. Spawning Frequency, Growth, and Mortality of Mytilus edulis Larvae, Exposed to Copper and Diesel Oil, Aquatic Toxicology 21, 171-180.

Swain, G., Kavanagh, C., Kovach, B., Quinn, R., 2001. The Antifouling Performance of Non-Toxic Silicone Fouling Release Coatings. In: Proceedings of Symposium on Prevention of Pollution from Ships and Shipyards. April 4-5, 2001. Miami, FL.

Swain, G., 2000. University Research on Antifouling Strategies and Environmental Considerations. Presentation to Alternative Antifouling Strategies Conference, September 21-22, 2000. San Diego, CA.

Swedish Chemicals Inspectorate, 2004. For a Non-Toxic Environment. Available Online at: http://www.kemi.se/templates/Page498.aspx.

The Netherlands Ministry of Housing, Spatial Planning and the Environment. Environmental Inspectorate, 2004. Available Online at http://www2.vrom.nl/pagina.html?id=8701.

Trocine, R.P., Trefry, J.H., 1993. Toxic Substances Survey for the Indian River Lagoon System. Florida Institute of Technology. Melbourne, FL.

U.S. Environmental Protection Agency, 2002. Total Maximum Daily Loads for Toxic Pollutants: San Diego Creek and Newport Bay, CA. U.S. EPA Region 9. San Francisco, CA.

U.S. Environmental Protection Agency, 2000. Establishment of Numeric Criteria for Priority Toxic Pollutants for the State of California Rule, 40 CFR Part 131, Water Quality Standards. Federal Register, May 18, 2000.

Valkirs, A.O., Davidson, B.M., Kear, L.L., Fransham, R.L., Zirino, A.R., Grovhoug, J.G., 1994. Environmental Effects from In-Water Hull Cleaning of Ablative Copper Antifouling Coatings. Technical Document 2662. Naval Command, Control and Ocean Surveillance Center, RDT&E Division. San Diego, CA.

VanderWeele, D.A., 1996. The Effects of Copper Pollution on the Bivalve, Mytilus edulis and the Amphipod, Grandidierella japonica in the Shelter Island Yacht Basin, San Diego Bay, California. M.S. Thesis. San Diego State University, San Diego, CA.

Fig. 1. Standard Maintenance Cost Properties: Copper-based and Epoxy Coatings

Property	Copper-Based Paints	Epoxy Hull Coatings
Application Frequency	Every 2-3 years	Every 7-8 years
Application Cost (per application)	$30/ft	$40/ft
Cleaning Frequency	14 times per year	22 times per year
Cleaning Cost (per application)	$1/ft	$1/ft
Stripping Frequency	Every 6th re-painting	Every 6th re-painting
Stripping Cost	$120/ft	$120/ft

Fig. 2. The Total Lifetime Cost of Maintenance for a New Boat