Antifouling Paints in Washington State: Third Report to the Legislature

Hazardous Waste & Toxics Reduction Program

Washington State Department of Ecology

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Contact Information

Hazardous Waste & Toxics Reduction Program

Washington State Department of Ecology
P.O. Box 47600
Olympia, WA 98504-7600

Telephone: 360-407-6700

Website: Washington State Department of Ecology[1]

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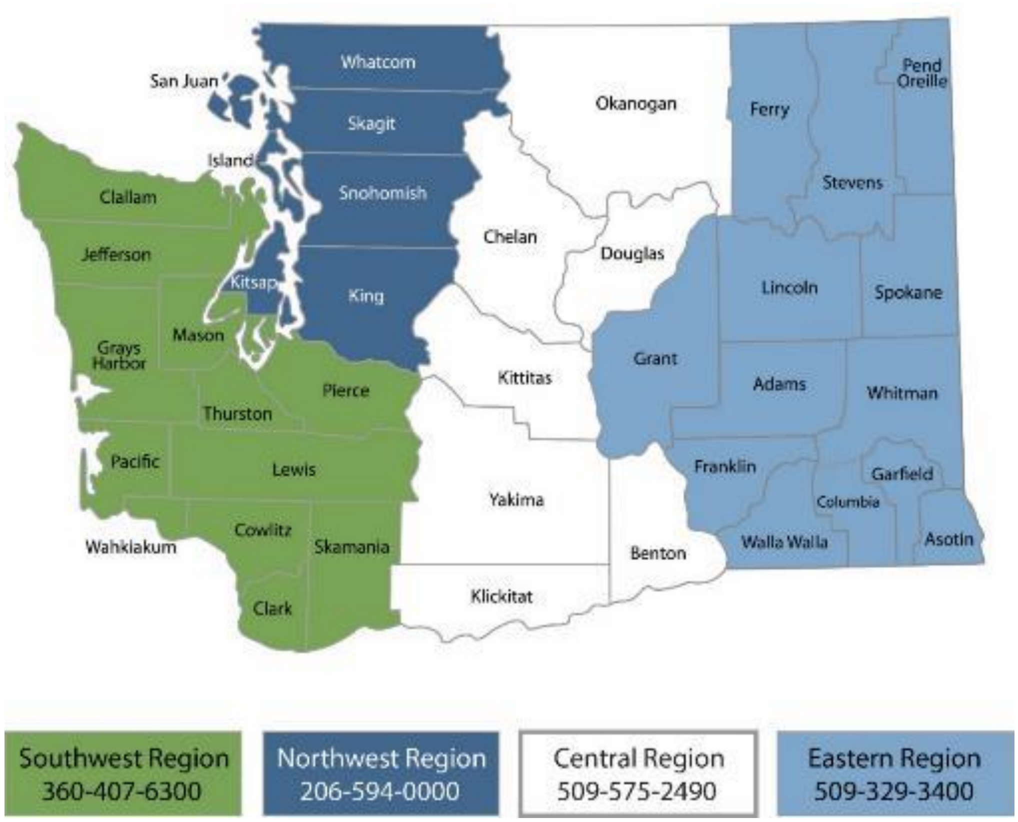

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Headquarters	Across Washington	PO Box 46700 Olympia, WA 98504	360-407-6000

Antifouling Paints in Washington State: Third Report to the Legislature

Pursuant to RCW 70A.445.020

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Executive Summary

Boats moored in marinas and other waterbodies provide a suitable surface for organisms to attach and grow. The undesirable accumulation of organisms, including algae and barnacles, is known as marine fouling. Marine fouling can degrade boat hulls, reduce fuel efficiency, and help spread invasive species. To prevent these effects, boaters use antifouling paints to either prevent fouling organisms from attaching or make it easier for them to dislodge. Antifouling paints often rely on biocides and other toxic chemicals to work.

Copper-based boat hull paint has been the most popular antifouling biocide additive in the market since the 1980s. Ecology's earlier work found that copper can impact water quality and marine organisms, including salmon. Washington has concerns about the release of copper and other toxic chemicals into the aquatic environment.

In 2011, the Washington Legislature passed legislation to phase out the use of copper-based antifouling paints. That legislation directed Ecology to conduct a survey in 2017 to investigate the availability and environmental impact of alternative antifouling products. Subsequent legislation directed Ecology to do a follow-up review of antifouling paints in 2019. Both reviews concluded that some non-copper alternatives might be more harmful to the environment than the copper-based paints. As a result, the Legislature delayed restrictions on copper-based paints. In 2020, Ecology was again directed to continue searching for safer and effective alternatives to copper.

This report summarizes the results of Ecology's latest review. It consists of a scientific review of biocidal and non-biocidal paints and ingredients. Biocidal paints contain chemically active ingredients which deter or kill marine organisms that attempt to attach to the hull. Non-biocidal paints rely on other working mechanisms, such as ultra-smooth surfaces, to make it difficult for organisms to adhere to. This report focuses on new scientific information that recently became available. It also explains our efforts to develop hazard-based criteria to objectively determine when antifouling chemicals are safer than existing options.

During our review of biocidal ingredients, we found non-copper antifouling biocides registered for use in Washington have remained essentially unchanged since our last review in 2019. Based on the new scientific information reviewed, Ecology concluded one non-copper alternative, DCOIT (Dichlorooctylisothiazolinone), is a safer chemical than copper, but we lack sufficient data to fully evaluate its effectiveness.

We reviewed research and studies related to non-biocidal paints, which are still in early development. Non-biocidal paints are emerging products designed for commercial vessels. A very limited number of products are available for recreational boats now. Currently available information suggests that non-biocidal paints primarily use silicone polymers or fluorinated chemicals, which may pose their own hazards. Most of the needed scientific information on environmental impacts is not yet available.

At this time, Ecology is not able to determine “that safer and effective alternatives to copper-based antifouling paints are feasible, reasonable, and readily available” pursuant to RCW 70A.445.020. As a result, the potential restrictions on copper-based paints in RCW 70A.445.020(3)(a)–(c) will not take effect in 2026, and Ecology will conduct a second review of relevant studies and information. A follow-up report will be submitted to the Legislature by June 30, 2029.

Antifouling Paints in Washington State

Legislative directive

RCW 70A.445.020 directs Ecology to conduct the following work:

> (1) The department will conduct a review of information about antifouling paints and ingredients, including information received from manufacturers and others pursuant to this chapter; information on the feasibility of best management practices and nonbiocidal antifouling alternatives; and any additional scientific or technical information and studies it determines are relevant to that review.
>
> (2) The department must submit a report to the legislature summarizing its findings no later than June 30, 2024. Prior to submitting the report to the legislature, the department will conduct a public comment process to obtain expertise, input, and a review of the department's proposed determinations by relevant stakeholders and other interested parties. The input received from the public comment process must be considered before finalizing the report.

This report is submitted to fulfill the above requirements.

Legislative history

Washington has a long legislative history concerning copper antifouling paint. In 2011, due to concerns about copper's potentially adverse impact on salmon, Chapter 70A.445 RCW[3] was enacted. The law restricted the use of copper-based antifouling paint for recreational vessels starting in 2018. The law also directed Ecology to survey types of antifouling paints sold in Washington to study how antifouling paints affect marine life and water quality, and then report the findings to the Legislature. In 2017, Ecology's report focused on available non-copper antifouling paints and showed that the use of biocidal alternatives to copper might have significant environmental impacts (Ecology, 2017).

In 2018, the Washington Legislature delayed the implementation of the ban until 2021 and directed Ecology to conduct further studies about the environmental impacts of antifouling paints and their ingredients, as well as explore safer alternatives to copper-based antifouling paints. In response, Ecology performed a modeling study on Washington marinas and reviewed applicable scientific publications. The follow-up report, completed in 2019, found that non-copper antifouling paints may pose a greater threat to the environment than copper-based paints (Ecology, 2019).

In 2020, the Legislature amended the existing law in response to Ecology's 2019 report and recommendations. The 2020 legislation adopted new restrictions on the use of an antifouling ingredient called Cybutryne and directed Ecology to continue reviewing relevant information about antifouling paints and ingredients.

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[3] https://apps.leg.wa.gov/rcw/default.aspx?cite=70A.445

Background

When structures are immersed in the marine environment, they are subject to various organisms that live in those waters. As these microorganisms (such as bacteria, diatoms, and algae spores) attach and settle, they create a slimy living layer, which provides a suitable environment for larger organisms to attach and grow. This natural phenomenon is known as marine fouling.

Over time, the accumulation of marine organisms leads to the formation of thick, rough, and irregular coatings on surfaces. When it happens on boat hulls, marine fouling can cause surface degradation, increased roughness, and higher fuel consumption, which is a major economic and environmental concern. If the aquatic species is invasive or non-native, recreational boaters can inadvertently spread the species to new locations.

To prevent fouling, boat owners use hull paints divided into two main categories: biocidal and non-biocidal paints. Biocidal paints have pesticides and other toxic chemicals to either prevent fouling organisms from attaching or to slow down their growth. Copper is the most common biocide in paint. Non-biocidal paints work by creating an ultra-smooth or durable hard surface that is easy to clean. Some non-biocidal paints don't have an antifouling function but support other antifouling practices, such as cleaning.

Copper

Copper has been the dominant active ingredient in antifouling paints since the phase out of tributyltin and is effective at killing many different types of fouling organisms. These hull paints generally rely on the leaching of copper to create an effective dose. However, as a result of long-term use in overloaded areas, elevated copper concentrations can occur in confined waters such as marinas. The maintenance on hulls can vary from pressure washing, sanding, grinding, or scraping to painting. During these processes, copper from antifouling paints may enter stormwater runoff.

Elevated copper in marine environments can cause acute toxicity such as mortality of aquatic species. Chronic exposure can lead to adverse effects on survival, growth, reproduction as well as alterations of brain function, enzyme activity, blood chemistry, and metabolism (US EPA, 2023).

There are federal and state regulations on copper antifouling paints. Copper-based antifouling ingredients are regulated as pesticides by the Washington State Department of Agriculture and the United States Environmental Protection Agency (EPA) under authority from the Federal Insecticide, Fungicide, and Rodenticide Act. Starting in 2019, EPA adopted a "maximum allowable leach rate" for antifouling paints for recreational vessels that contain copper. These paints may not release more than 9.5 micrograms (µg) of copper per cm^2 of painted surface per day, or else they do not qualify for registration (US EPA, 2018).

In Washington, boatyards monitor copper and zinc releases to stormwater runoff as a requirement under the Boatyard General Permit. In the 2022 re-issuance of this permit, the maximum daily benchmark value for total copper decreased from 147 µg per liter to 44 µg per liter in stormwater runoff discharged to marine surface waters of the state. Copper is listed as a Chemical of Concern[4] in Puget Sound.

Biocidal paints

Biocidal paints contain one or more chemically active and potentially lethal ingredients. The ingredients, known as biocides, can repel marine organisms, inhibit their growth, or limit their settlement. Most coatings contain an inorganic copper-based primary biocide, such as cuprous oxide, together with one or more organic booster biocides or co-biocides (Paz-Villarraga et al., 2022).

All biocidal paints used in Washington must be registered with EPA and the Washington State Department of Agriculture. The pesticide registration information in Washington is available to the public through the Washington State University's Pesticide Information Center Online Database.[5] A review of this database confirms that copper-based biocides are in 73 out of 87 registered products.[6] Cuprous oxide is the form of copper used most often. Other forms of copper are used as ingredients in antifouling paints, such as cupric oxide, copper pyrithione, and cuprous thiocyanate. Copper-free biocidal ingredients registered for use in Washington are limited to Tralopyril, zinc pyrithione, and DCOIT (Dichlorooctylisothiazolinone).

In addition to biocides, antifouling paints usually use other compounds in the formulations. Regardless of whether copper is the sole active ingredient or used in conjunction with other biocidal ingredients, the amount of copper released into the water from these paints is limited by the "maximum allowable leach rate."

Non-biocidal paints

In response to increasing concerns and regulatory pressures related to biocides, the paint manufacturing industry is actively conducting research to develop effective copper-free and biocide-free paints. Non-biocidal paints contain silicone, ceramic, or epoxy material. These paints are categorized into three types based on their working mechanisms:

- **Foul release coatings:** Foul release coatings are the leading market alternatives to traditional biocidal coatings. They create a smooth surface that does not dissolve in water. Foul release coatings work by preventing the attachment of fouling organisms through physical rather than chemical action. These coatings have either silicone elastomer, fluoropolymers, or a combination of the two, to create non-stick properties (Hu et al., 2020). Since fouling organisms are weakly attached to hulls, they can be removed by the force of the water during cleaning or navigation (Ciriminna et al., 2015; Lagerström et al., 2022).
- **Biocide-free self-polishing coatings**: This type of paint is water soluble and ablative, meaning it slowly melts away, like a bar of soap. It uses a combination of chemical

[4] https://ecology.wa.gov/Water-Shorelines/Puget-Sound/Issues-problems/Toxic-chemicals
[5] https://picol.cahnrs.wsu.edu/Search/Quick
[6] Registration information may change over time. This data only reflects a snapshot of registration information obtained from the pesticide database in August 2023.

action (such as hydrolysis) and mechanical action (for example, movement) to regenerate a new and smooth surface. During navigation, the coating goes through a progressive thinning process and continuously releases the upper layer to which organisms attach themselves (Lagerström et al., 2022).

- **Hard surface treated composite coating**: Hard coatings are made of durable materials that are resistant to aggressive cleaning, such as epoxies, polyesters, vinyl esters, or ceramic-epoxy compounds. These materials don't have direct antifouling functions but can be used in combination with heavy washing. It requires routine and timely cleaning, to prevent fouling build-up (Venettacci et al., 2023).

Even though a few soft paints including foul release coatings and biocide-free self-polishing coatings are commercially available, they are primarily developed for commercial vessels and propellers rather than recreational boats.

Scope and approach for this study

In developing this report, Ecology was directed by the Legislature to collect, review, and summarize available and relevant information about antifouling paints and ingredients.

- We limited the review to antifouling paints and ingredients that can potentially be used on recreational vessels working in marine environments and closely connected freshwater environments, as these are the types of vessels covered by the underlying statute.
- We relied on sources of information including peer-reviewed scientific studies, chemical assessments, government publications, and other published technical documents.
- We focused on studies or publications that discuss the efficacy of antifouling paints, the bioavailability and toxicity effects of ingredients, environmental impacts, alternative assessments, risk assessments, and best management practices for antifouling.
- Our review is limited to scientific evidence that became available since the completion of Ecology's 2019 report.

As a follow-up to Ecology's two earlier efforts, this report focuses on new and updated scientific evidence. This report does not summarize the findings from every study we reviewed. Instead, we extract and present only the most valuable information that may help in making informed decisions or charting the path forward toward identifying the best antifouling solution.

In the continuing search for alternatives to copper-based paints, we consider reducing hazards and achieving desirable performance as the current top priorities. The Legislature directed Ecology to determine whether safer and effective alternative chemicals to copper are feasible, reasonable, and readily available but did not provide statutory definitions. We used definitions from alternative assessment guides and other Ecology programs like Safer Products for Washington[7] to help define parameters. The Safer Products for Washington has established

[7] https://ecology.wa.gov/waste-toxics/reducing-toxic-chemicals/washingtons-toxics-in-products-laws/safer-products

methods for identifying safer alternatives that have been subjected to both peer review and a robust public involvement and comment process.

Safer antifouling chemicals are less hazardous to non-target species, do not persist in the environment for long periods, do not accumulate in human and animal tissues, and release fewer toxic chemicals into the environment. It is important to acknowledge that biocidal paints are designed to kill or harm target species. This primary function of antifouling ingredients makes them hard to be recognized as a “safe” chemical when using standard hazard assessment and certification standards. Based on these considerations, we developed criteria for what constitutes a “safer” antifouling alternative based on earlier Ecology work under the Safer Products for Washington program. We include this criteria in this report.

We also draw on methods developed for Safer Products for Washington to define **feasible** and **readily available**, which are based on the Interstate Chemicals Clearinghouse’s Alternatives Assessment Guide v1.1. Using this method, “feasible” and “available” alternatives are those alternatives that are already used to provide the same or similar antifouling function as copper boat paint. “Feasible” and “available” alternatives can also be alternatives that are offered for sale to prevent fouling at a price that is close to the price of current paints.

“Effective” and “reasonable” have not been used as metrics in other Ecology alternatives assessments. We consider “effective” and “reasonable” to be more stringent versions of feasibility and availability.

Effective alternatives, on a product level, can provide antifouling function in cold water and have a reasonable product lifetime. Most available product test data we identified were performed in warm-water locations. To understand the efficacy of antifouling paints in Washington, we collaborated with a research team at Washington State University to conduct a performance field test of already available paint alternatives. The performance test uses industry standard methods and rates each product with a score based on fouling coverage and types of fouling, as developed by the American Society for Testing and Materials (ASTM, 2020). The research team compared the performance score with the control product and copper-based paints to assess the effectiveness.

We define **reasonable** alternatives as those that can be easily adopted by many applicators. These alternatives will already be relatively available within the market or can become readily available to meet demand. Additionally, the alternative should be generally applicable to recreational boats made from different materials, or there should be sufficient distinct alternatives such that there is at least one safer, feasible, available, and effective alternative for all styles of recreational boats.

Criteria for Safer Antifouling Chemicals

Definition

Antifouling boat paints containing active ingredients may release harmful chemicals into the aquatic environment, causing contamination of wildlife and environmental resources. However, we have limited tools to differentiate those ingredients and identify safer alternatives based on their negative impacts on the environment or humans. Chapter 70A.445 RCW[8] requires Ecology to conduct a review of information to search for safer and effective alternatives to copper-based antifouling paints used on recreational vessels.

To establish a standard approach for future assessment, we developed a hazard-based criteria for "safer" based on the framework created for the Safer Products for Washington program, under chapter 70A.350 RCW.[9] This criteria is based on the Safer Products for Washington minimum and additional criteria for "safer," tailored to address the specific challenges posed by a product that is inherently and purposefully toxic. When new chemicals become available in the market, we can use this criteria as a starting point to determine whether it's safer or not.

As noted above, antifouling chemicals are biocides regulated under the federal and state law. These regulations require review of the major risks to people or the environment during the registration process.

The antifouling paint law does not provide a definition for "safer." Generally, we define "safer" as, "Less hazardous to the humans or the environment than the existing chemical or process," just as we do under the Safer Products for Washington program. Antifouling chemicals are considered "safer" when they:

- Are less hazardous to non-target species
- Are less persistent and accumulate less in tissues of humans, animals, and plants
- Release fewer toxic chemicals into the environment

Scope

Our criteria are based on hazard assessment rather than risk assessment. We evaluate "safer" through a chemical-to-chemical comparison in terms of their potential harm to the environment or human health. Therefore, the criteria cover a broad spectrum of hazard endpoints (like toxicities observed in various systems such as human skin, eyes, or the environment) to answer whether an alternative is "safer."

Another difference between our hazard assessment-based approach and a risk assessment is that exposure or other factors that are considered when doing a risk assessment are not the focus of our criteria for "safer." Our criteria include certain special considerations related to exposure, as they are critical to the use of antifouling chemicals.

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[8] https://apps.leg.wa.gov/rcw/default.aspx?cite=70A.445
[9] https://app.leg.wa.gov/RCW/default.aspx?cite=70A.350

Relevant information from risk assessments done by EPA and other agencies noted in the Review section of this report were reviewed in preparation of this report.

The "safer" criteria focus on alternative chemicals that provide the antifouling function. Only active ingredients supplying antifouling functions are considered, as it is assumed that paint formulations will be similar except for these ingredients. Inactive ingredients (such as solvents, plasticizers, or catalysts) were not considered. This document is intended to serve as guidance for the comparative assessment of antifouling chemicals used in boat paints.

Evaluation of inactive chemicals, chemicals with other functions, or chemicals used on structures other than recreational boat hulls is not within the scope of this review.

We acknowledge that regulatory requirements may evolve, and new toxicological information and scientific evidence may emerge over time. Therefore, it may become necessary to revise the safer criteria accordingly.

Approach

Our criteria focus on chemicals, not products or processes. The approach for identifying safer alternative chemicals involves utilizing the hazard criteria as described in the Safer Products for Washington Regulatory Determinations Report to the Legislature[10] with modifications and special consideration (Ecology, 2021a). The criteria include both minimum criteria and additional requirements. Figure 1 demonstrates the general process to determine chemicals as safer.

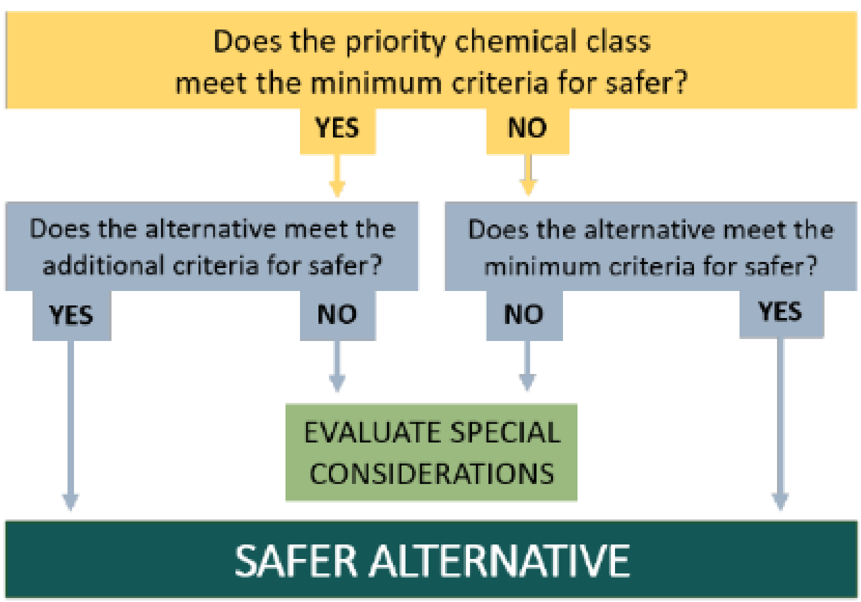

Figure 1: Flow chart overview of the general process used to determine whether alternatives are safer (Ecology, 2021). See the plain text version in Appendix C.

[10] https://apps.ecology.wa.gov/publications/SummaryPages/2204018.html

The minimum criteria for “safer” is a baseline set of hazard criteria and data requirements derived from GreenScreen® Benchmark-2 criteria for organic chemicals. The additional criteria for “safer” are derived from GreenScreen® Benchmark scoring system and the EPA’s Safer Chemical Ingredients List master criteria.

GreenScreen® for Safer Chemicals is a method of comparative chemical hazard assessment. Entities such as Organization for Economic Cooperation and Development, National Research Council, and Interstate Chemical Clearing House have used this tool to develop alternative assessment guidelines. Ecology has used this hazard assessment tool in multiple studies to identify chemicals of high concern and safer alternatives since 2008.

In the GreenScreen® for Safer Chemicals methodology, chemicals receive a combined "benchmark score" based on the assessments of 18 hazard endpoints, such as whether they cause cancer or are toxic. For each hazard endpoint, the chemical is scored as Very Low, Low, Moderate, High, or Very High. The final result is a single GreenScreen® Benchmark scores are as follows:

- Benchmark-1 – Avoid: Chemical of High Concern
- Benchmark-2 – Use but search for Safer Substitutes
- Benchmark-3 – Use but still opportunity for improvement
- Benchmark-4 – Prefer: Safer Chemical

These scores are typically referred to as BM-1, BM-2, BM-3, and BM-4, respectively. When not enough information is available to evaluate the hazard, a Benchmark-Unknown (BM-U) score is given.

We use the same process and criteria to compare alternative chemicals to copper-based antifouling chemicals. The Safer Products for Washington “safer” criteria are applicable to any organic (that is, carbon-based) chemical. Although copper-based chemicals are inorganic, all alternatives to be considered are organic chemicals. This allows us to use the Safer Products for Washington criteria to identify safer antifouling chemicals. In rare cases where inorganic alternative chemicals are to be assessed, these criteria will be modified based on the GreenScreen® criteria for inorganic chemicals (as we did for copper).

Copper oxide, also known as Cuprous Oxide or Cu_2O, does not meet the minimum criteria for safer based on its GreenScreen® Score of BM-1. It has Very High aquatic toxicity and Very High persistence. A further review of the data confirmed that most of the data used for ecotoxicity classification are from non-target species such as fish and freshwater green algae.

Based on the decision-making process, alternatives to copper oxide must meet our minimum criteria to be safer. Only chemicals that align with the GreenScreen® BM-2 category or better will be further considered.

Modifications and special considerations

Additional data review with emphasis on non-target species

The hazard endpoint and data requirement for assessment are outlined in Table 1.

Table 1: Hazard endpoint and data requirement (not all endpoints are required).

Hazard endpoint	Required to make a Benchmark determination
Carcinogenicity (causes cancer)	Always required
Mutagenicity/Genotoxicity (causes mutations or damages DNA)	Always required
Reproductive or Developmental Toxicity	Always required
Endocrine Disruption	Not required
Acute Toxicity	Not always required*
Single or Repeat Systemic Toxicity	Not always required*
Single or Repeat Neurotoxicity (toxic to the neurological system)	Not always required*
Skin or Respiratory Sensitization	Always required
Skin or Eye Irritation	Not required
Acute or Chronic Aquatic Toxicity	Always required
Persistence (does not break down in the environment)	Always required
Bioaccumulation (accumulates in tissue of an organism)	Always required

***Two of three endpoints with asterisks are required**

Among the required data, acute or chronic aquatic toxicity is particularly important. However, for purposes of this review, we needed to make some changes to accommodate the inherently toxic nature of antifouling ingredients.

The most important change we made was to incorporate additional data review in our minimum criteria for "safer." This modification means that we classify hazard levels based only on non-target species data instead of all available comprehensive data. Since antifouling chemicals are designed to be toxic to the target organisms, they are more likely to fail to meet minimum criteria due to their efficacy. We concluded that hazard assessments for antifouling chemicals that don't treat target and non-target organisms differently may result in misleading conclusions. Standard marine toxicity tests usually measure lethal and sublethal effects on species that are not typical fouling species.

To support this additional data review, we define target organisms for antifouling chemicals as typical marine plants and sessile animals (like barnacles) that are commonly found in biofouling communities. A group of representative biofouling organisms is identified as the target species in Table 2. These species are summarized from the literature studying the biofouling communities on boat hulls, or model biofouling species used for toxicity studies (WDFW, 2016; Willis et al., 2007; Rasmussen et al., 2001; Tang et al., 2021; Mitbavkar et al., 2008; Zargiel et al., 2011; Chung et al., 2019; Dobretsov et al., 2021; Thiyagarajan et al., 2016). We consider any experiment data or modeling data that are performed on the defined "non-target" species as relevant data in the additional data review.

As noted, the list is not comprehensive and intentionally excluded bacteria, protozoa, and more motile organisms. The biofouling organisms on boat hulls are extremely diverse. We define the most representative biofouling species in the table below. We assume those not listed will be mostly non-target species. Organisms considered non-target organisms include fish, sea urchins, shrimp, or any freshwater organisms.

Table 2: A list of target organisms for antifouling chemicals.

Common Name	Description
Fungi	Microfouling organisms. Marine filamentous fungi are commonly associated with algal species.
Microalgae algae - Diatom	Dominant microfouling organisms secreting sticky extracellular mucilaginous substances which can form a compact biofilm and further promote bioadhesion.
Macroalgae	Common microfoulers including green, red, and brown algae. They are eukaryotes and photosynthetic as primary producers for biofouling community.
Barnacles	Key macrofouling organisms, primary invertebrate model for biofouling.
Bryozoan	Colonial animals, many single zooids are stitched together to make one larger colony.
Mollusks	Invertebrate animals.
Polychaete	Sessile, tube-building annelid worms, or worms with coiled shells. Usually live attached to substrates.
Tunicates	Marine invertebrate animals.
Sponge	Sessile filter-feeder animals.
Hydroid	Very small, predatory marine animals.

Concerns about salmon

In Washington, one of the motivations to phase out copper in antifouling paints is to protect culturally and ecologically important species, such as salmon. The sublethal effects of copper on Coho salmon, and particularly on the salmon's sensory function, have been well documented in freshwater environments (Baldwin et al, 2003; McIntyre et al., 2008, 2012; Sandahl et al., 2007; Hecht et al., 2007). The dissolved copper's effect on salmonid olfaction in saltwater environments remains a recognized data gap. As mentioned in the scope, these safer criteria use hazard assessment to determine how toxic the chemical is, and the environmental difference is a factor in exposure, which is considered in risk assessment. The potential differential impact on salmon olfaction in marine versus freshwater environments doesn't fundamentally alter the hazardous classification of the chemical. Salmon are a sensitive non-target species. Based on our criteria, all salmon-related toxicity data that meets the data requirement will be included in the assessment. No additional modifications are required for using available toxicity data from salmon.

Special considerations

When an alternative antifouling chemical is identified to be potentially safer, based on our criteria, we continue to review its magnitude of exposure potential. The copper oxide and alternative chemicals in this document are direct-release chemicals with similar exposure routes. The magnitude of exposure potential has a direct impact on the aquatic environment. We considered the leaching rate, migration, and typical concentrations of the chemicals used in products.

Review of Antifouling Paints and Ingredients

Biocidal ingredients

Copper

Copper is listed as an ingredient in 73 out of 87 antifouling paints registered for use in Washington. Approximately 80 percent of recreational vessels are painted with copper-based paints.

Bioavailability and toxicity of copper

Our findings about copper's bioavailability and aquatic toxicity are consistent with the conclusions from the two earlier Ecology reports. Copper is moderately bioaccumulative and is very toxic to aquatic organisms at elevated levels.

In water, copper may exist as free ions or become part of complexes with various complexing chemicals that interact with metals. Physicochemical characteristics of the exposure water can affect copper speciation, and therefore affect the toxic amounts of bioavailable copper. While copper is a common micronutrient found in water, the elevated levels of copper from antifouling paints and other resources cause problems in aquatic environments.

New scientific studies reported copper's toxicity effects on a wide range of non-target organisms, including zebrafish, copepod, mussels, common cockle and harbor ragworm, flatworm, tanaid and amphipod, marine medaka, and Pacific oyster (Santos et al., 2021; Molino et al., 2019; Cao et al., 2019; Zitoun et al., 2019; Young et al., 2023; Muller-Karanassos et al., 2021; Ma et al., 2020 ; Soroldoni et al., 2020; Wang et al., 2020b).

In addition, some studies reported the toxicity at a systematic level, finding negative impacts to marine invertebrate communities, species living in aquatic sediment and overall species diversity (Miller et al., 2020; Schaanning et al., 2019; Cima et al., 2022b).

Source tracking of copper

Other recent studies focused on monitoring copper leaching from bottom paints and looking for associations between copper concentrations and the use of antifouling paints (Morling et al., 2021; Carić et al., 2021; Thanh et al., 2021). A point source study in the United Kingdom looked at the estuarine copper concentrations near a boat wash-down site. This study found that copper can be diluted in the estuary within four hours. However, the copper levels at half a meter away remained 10- to 20-fold elevated above the levels sampled from 30 meters away from the source (Chadwick, et al., 2023). Another study traced copper from antifouling paints to shipyard sludges and sediment cores in Port Camargue, France (Briant et al., 2022). These studies further confirmed our earlier findings, showing copper-based antifouling paints can significantly contribute to the amount of copper in the marina environment.

In summary, copper is very toxic to non-target aquatic species and persistent in water and sediment. Copper from antifouling paints significantly contributes to the copper in the marina environment.

Non-copper

Three non-copper biocides are currently available on the market and approved for use in Washington: Tralopyril (also sold as Econea), zinc pyrithione, and DCOIT (also known as Sea-Nine). Ecology partnered with researchers from Washington State University to review scientific literature about the toxicity of these biocides, with an emphasis on non-target species (Mahmoodi et al., 2023).

Tralopyril/Econea

Tralopyril, marketed under the brand name Econea, was approved for use in the United States in 2007 and in the European Union in 2014. It is listed as an ingredient in 11 out of 87 products registered for use in Washington, typically at a concentration of 6%.[11] Tralopyril is an organic synthetic biocide and can kill a broad range of fouling organisms. It is marketed as non-persistent and biodegradable.

Tralopyril hydrolyzes, or breaks down, in water rapidly, with a half-life of 7.4 hours in saltwater at 17°C (Lavtizar et al., 2019). However, recent research reported that the two main hydrolysis products of Tralopyril exhibited exceptional resistance to biodegradation. These breakdown products became persistent chemicals in the water-sediment systems (Koning et al., 2021). Notably, the toxicity of those hydrolysis products is not fully investigated. Only one study reported that the two hydrolysis products, at 100 micrograms per liter, did not appear toxic to sea urchins (Lavtizar et al., 2019).

Tralopyril is highly toxic to aquatic organisms, including those non-targeted fish and invertebrates. Recent scientific studies have reported the toxicity effects of Tralopyril on non-target species including zebrafish, sea urchins, Pacific oysters, and turbot. The toxicity effects include disruption in thyroid system and metabolism, disruption in mitochondrial function, abnormal growth and calcium regulation, and impact on endocrine functions (Chen et al, 2022; Lavtizar et al., 2019; Wang et al., 2022; Liu et al., 2022).

In addition to persistence and ecotoxicity, Tralopyril may also impact human health, with very high acute mammalian toxicity, single exposure neurotoxicity, and developmental toxicity (ECHA, 2019).

Ecology didn't find any studies in Washington waters that can provide direct information about Tralopyril concentrations and environmental fate. However, Tralopyril and its degradation products are more stable at a lower temperature, indicated by a longer half-life. When Tralopyril is used near Washington coastlines with colder water, both highly toxic Tralopyril and the persistent degradation products can exist in water with prolonged stability. This can pose greater risks compared to the same products being used in a warmer environment.

In summary, Tralopyril turns into persistent chemicals after hydrolysis, exhibits high ecotoxicity, and poses concerns for human health risks.

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[11] Registration information may change over time. This data only reflects the information obtained from the pesticide database in August 2023.

Zinc pyrithione

Zinc pyrithione is one of the most frequently used alternative biocides to copper. A review of the pesticide database shows that 17 out of 87 products or brands include zinc pyrithione in the formulations. Most products use it as a co-biocide together with other active ingredients.

Zinc pyrithione is persistent in the environment, especially in the lower water column or in sediment where ultraviolet light is not available. It breaks down in the saltwater environment through photolysis (where light energy breaks the chemical bonds), with a short half-life of nine hours. The degradation products include zinc metal and the terminal pyrithione sulfonic acid. The zinc metal is expected to absorb into the sediment but the pyrithione sulfonic acid will be present in the water column with higher persistence than the parent compound (US EPA, 2020b).

Zinc pyrithione is toxic to a wide range of marine organisms. Multiple toxicity studies published since 2019 report adverse effects of zinc pyrithione on non-targeted species, including Mediterranean mussels, freshwater mussel, sea anemone, zebrafish, and sea urchin (Katalay et al., 2022; Gutner-Hoch et al., 2019; Třešňáková et al., 2020; Ünver et al., 2022;). For example, zinc pyrithione disrupts the endocrine system in zebrafish by affecting proteins in egg yolks (Günal et al., 2022).

Some ecotoxicity studies focused on target species. Zinc pyrithione exhibited the highest toxicity on some fouling species. It caused severe malformations in newly hatched swimming larvae of star tunicate, also known as sea squirts, a dominant species of soft fouling (Cima et al., 2022a; Lee et al., 2020).

In human health assessments, zinc pyrithione has high developmental toxicity, very high acute toxicity, and systemic toxicity. The classification, labelling, and packaging regulations in European Union rated zinc pyrithione as a chemical with high developmental toxicity in humans as “it may damage the unborn child” (EC SCCS, 2019). The recent EPA zinc pyrithione risk assessment stated that there are inhalation and dermal risks of concern for shipyard painters handling zinc pyrithione-containing antifouling boat paint (US EPA, 2020b).

In summary, zinc pyrithione is a persistent and toxic chemical. New information shows this chemical has significant human health risks, including developmental toxicity and inhalation and dermal risks.

DCOIT/Sea-Nine

DCOIT, commonly known as Sea-Nine, is an emerging biocide that was approved for use in the United States in 2015. There are currently seven products registered for use in Washington containing DCOIT. Among these, only one product was using DCOIT as the single biocide. The other products use DCOIT in formulations as a co-biocide.

DCOIT breaks down primarily through biological degradation. The half-lives of DCOIT in the environment (water, sediment, and soil) are noticeably short, ranging from a couple of hours to a maximum of 4.7 days (ECHA, 2018). The anerobic degradation half-life is less than one hour in seawater-sediment (EPA, 2020a). Meanwhile, its primary degradation product is readily biodegradable. This chemical has a high affinity for water[12] and is less likely to adsorb to organic matter, which means it tends to have a low bioconcentration factor.

DCOIT exhibits high and non-selective toxicity to marine organisms. In ecotoxicity studies, DCOIT can cause mortality, low hatching rates, disturbances in enzymes, cytotoxicity, and oxidative stress. Our reviewed information show that DCOIT can cause negative response in marine species such as the neotropical oyster, brown mussels, marine polychaeta, clams, sea urchin, brine shrimp, and pacific white shrimp (Campos et al., 2022, 2023; Gabe et al., 2021; Eom et al., 2019; Jesus et al., 2021; Su et al., 2019; Fonseca et al., 2020).

In several studies, DCOIT exhibited higher toxicity toward oyster embryos, and copepods nauplius than Cybutryne, an antifouling biocide being phased out worldwide and is already banned in Washington (Onduka et al., 2022; Hyun et al., 2022).

The latest EPA risk assessment indicates that DCOIT fails both the inhalation and dermal assessments by a wide margin for occupational painters. Thus, the concern for occupational exposure remains (EPA, 2020a).

Earlier monitoring studies have reported DCOIT in the seawater at parts per billion levels in Spain, Greece, Denmark, and Korea. The occurrence of DCOIT in marine environments is highly dependent on the monitoring location and sample matrix. Recent studies in Danish marinas and the Black Sea near Turkey reported that DCOIT was not detected in any samples (Koning et al., 2020; Çetintürk et al., 2022). Either dispersion or biological degradation may have resulted in a rapid decrease in the concentration. Other studies from Latin America and the Caribbean found DCOIT contamination to be the most frequently detected booster biocide found in the water and sediments (Almeida et al., 2023; Abreu et al., 2020; Uc-Peraza et al., 2022). We found no information about the environmental concentrations of DCOIT in Washington.

In summary, DCOIT exhibits high toxicity to many marine organisms, but it breaks down quickly in seawater and does not persist.

Summary of biocidal paints

Evaluation on "safer"

As noted above, only chemicals that align with the GreenScreen® BM-2 category or better can pass the minimum criteria and be considered as "safer." The decision-making process incorporates additional data review in the minimum criteria.

In our previous work, Ecology used GreenScreen® hazard assessment to compare alternative biocides to copper. Cuprous oxide received a BM-1 score. The alternative chemicals Tralopyril and DCOIT received a BM-2 in previous assessments. Zinc pyrithione received a score of $BM\text{-}1_{TP}$, where the subscript "TP" means that one or more transformation products (chemicals produced as the original chemical breaks down) drives the Benchmark score. GreenScreen® Benchmark scores, except BM-1, expire after five years.

[12] This chemical has a low octanol-water partition coefficient of 2.8.

Since the time of our last report, no new alternative biocides became available in the market. However, due to new data and information, GreenScreen® Benchmark scores for Tralopyril and zinc pyrithione have both changed to BM-1 from BM-2 and $BM\text{-}1_{TP}$,respectively. In Table 3, we summarize the most updated GreenScreen® assessments for a comparison among the four available biocides. The GreenScreen® assessments of Tralopyril and DCOIT were prepared by ToxServices, LLC for Ecology in 2023. We used the existing cuprous oxide assessment in 2020 and zinc pyrithione assessment in 2022, from Tox Screened Chemistry Library® maintained by ToxServices, LLC.

Table 3: GreenScreen® for Safer Chemicals summary hazard tables for biocides.

Key: vL = very low; L = low; M = moderate; H = high; vH = very high; DG = data gap; *italics = lower confidence*; **bold = higher confidences**

CAS #	Name	GreenScreen® Benchmark	Carcinogenicity (causes cancer)	Mutagenicity (mutates DNA)	Reproductive Toxicity	Developmental Toxicity	Endocrine Activity	Acute Toxicity	Systemic Toxicity	Systemic Toxicity, Repeated dose*	Neurotoxicity (toxic to nervous system)	Neurotoxicity, Repeated dose*	Skin Sensitization*	Respiratory Sensitization*	Skin Irritation	Eye Irritation	Acute Aquatic Toxicity	Chronic Aquatic Toxicity	Persistence (does not break down easily)	Bioaccumulation (builds up in tissue)	Reactivity (reacts easily with other chemicals)	Flammability (ignites easily)
1317-39-1	cuprous oxide	1	*L*	**L**	**L**	*M*	DG	**M**	*H*	**M**	DG	DG	**L**	*L*	**L**	*H*	**vH**	**vH**	*vH*	*L*	*L*	*L*
122454-29-9	Tralopyril	1	*M*	**L**	*L*	*H*	DG	**vH**	DG	**H**	*vH*	**H**	*L*	*L*	*M*	*M*	**vH**	**vH**	*vH*	**vL**	**L**	**L**
13463-41-7	zinc pyrithione	1	**L**	**L**	**L**	**H**	*M*	**vH**	*vH*	**H**	**M**	**H**	*L*	*L*	**L**	**vH**	**vH**	**vH**	***H***	**vL**	**L**	*L*
64359-81-5	DCOIT	2	**L**	**L**	**L**	**L**	*M*	**vH**	*vH*	**L**	DG	**L**	**H**	DG	**vH**	**vH**	**vH**	**vH**	***L***	*vL*	*L*	**L**

With new information, both Tralopyril and zinc pyrithione cannot pass the minimum requirements for “safer.” DCOIT, as a BM-2 chemical, passes the minimum criteria due to low persistence and very low bioaccumulation. We conclude from our hazard assessment that DCOIT is a safer antifouling chemical compared to copper. However, during the literature review, we found evidence showing acute and chronic toxicities of DCOIT on some non-target species.

Review on effectiveness

Based on our definition of effectiveness, the products can provide antifouling function with comparable performance to copper or control paints within the specified product lifespan. We searched for peer-reviewed literature, government publications, and independent sources for field efficacy tests. TechLaw and Northwest Green Chemistry contracted with Ecology to conduct an Alternatives Assessment in 2017 (TechLaw and NGC, 2017). This report evaluated paint performance based on a report from the Unified Port of San Diego and the Institute for Research and Technical Assistance and panel testing by Practical Sailor, supplemented by customer reviews from purchasing websites and boating forums (SDUPD and IRTA, 2011; Practical Sailor, 2023). We checked new information from similar resources and found limited updates. Ecology excluded customer reviews due to unverifiable data quality. The number and variability of data points are still an existing hurdle for us to draw conclusions.

In peer-reviewed literature, we found a study reporting field immersion tests at locations near the Mediterranean Sea and France for formulated paints using copper and booster ingredients. It concluded that the specific pattern for macrofouler (larger-size fouling organisms) assemblages depends on the location. The combination of DCOIT and cuprous oxide was able to prevent marine fouling for 16 months with similar performance to an established copper-based coating (Bressy et al., 2022).

Another peer-reviewed document reported results from efficacy testing of antifouling products for sea-based salmon farming based on the ASTM Standard method for testing antifouling panels in shallow submergence (ASTM, 2020). None of the products using Tralopyril or zinc pyrithione were able to prevent biofouling or performed better than the established commercial copper coating within the tested period (Bloecher et al, 2020). In a study on the Portuguese shore, a test from a real immersion scenario showed that products with Tralopyril performed better than a biocidal-free foul-release coating after two and half years (Silva et al., 2021).

A government report by the Netherlands National Institute for Public Health and the Environment concluded that there was a lack of reliable data on the effectiveness of alternative antifouling products in practice for pleasure boats in 2018 (Wezenbeek et al., 2018). A follow-up report in 2020 evaluated the efficacy of market-available products in both panel testing and boat testing. However, all tested products except one contained biocide. The non-copper biocidal product, Seajet ex3, was an experimental product pending registration. It was also the best-performing product in boat testing with regard to fouling prevention in saltwater (Klijnstra, 2020).

In our review, we focused on searching performance data on DCOIT-containing products. However, DCOIT is an emerging biocide and we found only one product contains DCOIT as the single biocide. Practical Sailor, an independent publisher, tested the new SN-1 high performance ablative paint that uses DCOIT. It concluded the product at 12 months to be “virtually slime-free, although some thinning of the coating was noted,” but “suffered a drastic decline at 18 months and was rated near the bottom of our group” (Practical Sailor, 2023). Most other products use DCOIT as a booster biocide, with copper oxide.

The performance data is limited and questionable for extrapolation to Washington waters because most of the panel testing was performed in warmer water. We were not able to verify the data quality from other data sources such as boating forums and customer testimonials. Due to limited data, we cannot conclude the effectiveness of DCOIT.

To fill this data gap, we collaborated with a research team at Washington State University and conducted a performance field test. The performance testing results are included in Appendix A of this report.

Other biocides

All biocides are subject to strict regulation through pesticides registration, both federally and at the state level. In addition to risk assessments done during in the initial registration, EPA reviews each registered pesticide at least every 15 years.

There are some other biocides registered for use in Europe and other countries. For example, Dichlofluanid, Medetomidine, Zineb, and Tolyfluanid are four additional biocides registered in Europe. Zineb and Tolyfluanid were cancelled for registration in US in 1980s and 2010s, respectively. Medetomidine was considered in our previous alternative assessment, but it was exclusively used for antifouling of barnacles and was classified very high for acute mammalian toxicity, receiving a GreenScreen® BM-1 score. Ecology doesn’t believe that other biocides for antifouling will be available and feasible in the near future to replace copper.

Non-biocidal alternative paints

Due to regulatory pressure and environmental concerns, more active research is shifting to focus on non-biocidal paints. Typical non-biocidal paints include foul release coatings, biocide-free self-polishing coatings, and hard surface treated composite coatings. Most of the time, these technologies have only been explored in labs and are not yet used on non-commercial vessels. Each of the non-biocidal paints have drawbacks, which either prevent the products from being more commercially available or limit the application to certain types of boats or conditions.

We believe that non-biocidal paints have not yet reached technological maturity and need more time for further development. We found that studies discussing the environmental risks and toxicities of these paints and ingredients are extremely limited.

Foul-release coatings

Foul-release coatings are the leading market alternatives to traditional biocidal coatings. However, the main drawback is idle periods and poor mechanical strength. Foul-release coatings depend on physical action, such as a vessel moving through the water, to “release” the weakly adhered organisms. These coatings work better for boats in constant or near-constant motion, such as commercial vessels. These coatings usually have silicone or fluoropolymer-based binders. Today, major coating companies market at least one biocide-free foul-release coating product and most of them are only available to commercial shipping market (Kim et al., 2021). Examples include:

- Silic One: Silicone based foul-release coatings for recreational vessels by Hempel A/S.
- B-Free Explore®: Silicone-based coatings for recreational vessels by international Marine Co.
- Intersleek 1100SR: Fluoropolymer-based biocide-free coatings by International Marine Co.
- Hull Maxx: Silicone based coatings by NASCO Worldwide, Inc.
- Sigmaglide 1290: Silicone based coatings by PPG Industries, Inc.
- SLIPS® Dolphin™: Foul-release coatings by Adaptive Surface Technologies, Inc.

No foul-release coatings were available for recreational use in the Washington market when this report was prepared. However, we received a public comment stating that one product will become available in the United States and Canada in 2024. Though foul-release coatings have started to be available in the market, their environmental impact is unknown. Manufacturers don't disclose their formulations, but all examples we identified included fluorinated chemicals and silicone oils, both of which can potentially cause negative environmental impacts.

For fluoropolymer based foul-release coatings, a 2021 California study found three out of four non-biocidal coatings contain high levels of per- and poly-fluoroalkyl substances (PFAS) ranging from 400 ng/L to 50,000 ng/L (Anghera et al., 2022). Another study by Nordic Council of Ministers identified that PFAS is used to make Intersleek 1100SR Part C (50%–75%) (Wang et al., 2020a). Commonly referred to as "forever chemicals," these fluorinated chemicals are pollutants of high concern in the marine environment. Washington restricts intentionally added PFAS in several consumer products due to concerns about persistence, bioaccumulation, and adverse human health impacts (Ecology, 2021b; Ecology, 2022). Ecology cannot support the use of PFAS as a substitute for copper in antifouling paints.

For silicone-based foul-release coatings, literature has mentioned that hydrophilic-modified silicone oils can leach from foul-release coatings. The leaching of persistent silicone oils could lead to the build-up of oil film on the sediments, and entrapment and suffocation of organisms that live in those environments.

In addition to PFAS or silicone oils, other substances leaching from foul release coatings are unknown. Substances that are being released to the environment could include catalysts, unreacted components that migrate to the surface of the polymer, solvents, or low levels of toxic compounds in pigments and other additives. Antifouling paint particles that contain these substances can contribute to marine contamination as microplastics. We lack sufficient information to draw conclusions about the toxicity and environmental impact of foul-release coatings.

Limited studies show that some of these products have superior performance compared to traditional copper coatings. A study on the Swedish west coast reported that Sigmaglide 1290 by PPG Industries led to significantly less fouling compared to self-polishing copper-containing paint (Oliveira et al., 2020). Similarly, another study in the Baltic Sea region reported that Hempel's Silic One performed equally well or significantly better than the studied copper coatings regardless of exposure site or time (Lagerström et al., 2022). However, the effectiveness of paints can vary tremendously from area to area. Ecology has no information on the efficacy of foul-release coatings in Washington. To address the data gap, we conducted performance testing in Washington and included two foul-release coatings that were available for commercial ships. No foul-release coatings were marketed for recreational vessels during the performance test.

Biocide-free self-polishing paints

Biocide-free self-polishing paints are not technically and economically viable yet. We found one product, Aquaterras by Nippon Paint Marine, marketed as the world's first biocide-free self-polishing coating. The composition and effectiveness of this paint is not clear. We found no scientific evidence for the safety, efficacy, and potential environmental risks of biocide-free self-polishing paints.

Hard surface treated composite coating

Biocide-free hard cleanable coating is used on leisure boats for antifouling. It uses durable materials that can withstand aggressive brushing once a month. This type of paint has the least environmental impact comparing to other paints. However, this type of paint requires frequent and regular cleaning cycles by brushes or hydro jetting (Waterman et al., 2019).

The use of hard coatings needs readily available and cost-effective cleaning stations and mobile cleaning services. Hull cleaning services in Washington are provided by haul-out facilities. It is illegal to perform underwater hull cleaning on recreational vessels that use soft ablative or sloughing paints. Drive-in boat wash stations are not available in Washington. Commercial vessels' washing efforts must follow Washington's Guidance on Hull cleaning in Washington State Waters.[13] Recreational vessels aren't covered under this guidance.

Other alternatives

In our earlier report, Ecology identified other emerging alternatives such as natural antifouling products derived from marine microorganisms and invertebrates, or natural superhydrophobic materials from plants. Since 2019, researchers have conducted more laboratory-scale or sea-trial research on natural product-based ingredients or biomimetic antifouling surfaces (Yan et al., 2020; Hao et al., 2022; Liu et al., 2020). However, major challenges remain in the commercialization of natural products. For example, the process to extract active ingredients from raw materials on a large scale before they can be added to the coating formulations can be technically difficult. Natural products are not necessarily safer than synthetic chemicals. The effectiveness, safety and toxicity of natural products still need verification through substantial

[13] https://wdfw.wa.gov/sites/default/files/2019-03/ecy_hull_cleaning_guidance_14-10-012.pdf

scientific data. There is a long way to go for natural products to be technically successful, in terms of structure optimization, stability, and coating incorporation.

Other than using antifouling paints, recreational boats can use other non-paint options to tackle marine fouling. Smaller boats, shorter than thirty feet, can be removed from water entirely using a lift or trailer. Boats in a permanent mooring can use options such as washing systems, liners, in-water dry docking, and sonic-based systems.

Cleaning in haul-out facilities is a highly effective antifouling technique with less environmental impact. In Washington, we still have some barriers, such as permitting challenges for in-water boat washes or the availability of cleaning facilities and infrastructure. Supporting the development of diverse cleaning solutions can provide more antifouling tools and help minimize the environmental impacts from using antifouling paints.

Non-coating alternatives alone cannot practically solve the fouling problem. We recognize that including coatings as part of the strategy will be necessary. Antifouling paints used in combination with non-coating alternatives such as boat lifts, dry docks, and cleaning can minimize the potential for adverse environmental impacts.

Feasibility of best management practices

The use of best management practices to control copper discharges from point sources (boatyards) or non-point source (marinas and harbors) can significantly reduce the overall pollution from antifouling paints. Marinas, boatyards, and harbors with heavy boat traffic are the most vulnerable areas to a heavy loading of copper, other biocides, and microplastics from paints. These chemicals might reach concentrations that affect the ecological health of the water body.

Without the use of best management practices, the wastewater and stormwater discharges from point sources like boatyards and other similar facilities can exceed water quality standards (Crowser, 1997). For antifouling paints, facilities can implement best management practices for point source discharges control during the painting, cleaning and maintenance upland or in-water.

The current Boatyard General Permit in Washington requires the implementation of several mandatory best management practices to manage pollution from pollution sources, including copper antifouling paint.

- It prohibits the discharge of pressure washing wastewater directly to waters of the state and requires that pressure wash areas are decontaminated after use.
- It requires vessel hulls only be sanded using vacuum sanders to collect dust, places restrictions on in-water maintenance and hull work, restricts upland vessel maintenance activities, and mandates proper management of solid wastes, including paints, solvents, and other chemicals.
- It sets several different limits and benchmarks that restrict the discharge of copper in wastewater or stormwater.

The most recent version of the Boatyard General Permit (2022) reduces the limit for copper content in wastewater discharged to a non-delegated publicly owned treatment works, and the benchmark for stormwater discharged to surface waters. When source control best management practices are not enough to control stormwater pollution at a boatyard, the permit can require the facility to install stormwater treatment to remove copper and other pollutants from the water prior to discharge.

The permit states, "Permittees must prepare a handout describing these best management practices and provide copies to all employees, contractors, boat owners, and other customers, as appropriate." The permit requires the list of best management practices in a facility specific document called the Stormwater Pollution Prevention Plan.

Annual monitoring of stormwater is required to verify the effectiveness of best management practices, since Boatyard Permits were first issued in 1992. Best management practices listed in the permit are developed and improved over time. The permit is re-issued every five years. We believe the current best management practices are efficient and feasible in minimizing or eliminating the discharge of pollutants originated from antifouling paints from boatyards.

There are effective best management practices for controlling non-point sources of copper pollution. In-water hull cleaning of boats is banned in Washington. Commercial vessel ship hull cleaning is allowed under the Vessel General Permit (soon to be replaced with "Vessel Incidental Discharge Act). State specific guidance can be found in the Focus on In-Water Hull Cleaning publication,[14] issued in 2014.

[14] https://apps.ecology.wa.gov/publications/SummaryPages/1410012.html

Performance Testing of Antifouling Paints

Introduction

Over the past decade, the paint industry has developed many new antifouling paint products, including non-copper alternatives. Due to the establishment of copper in the antifouling market, many boat owners and boatyard operators are hesitant to switch to non-copper alternatives, with concerns about the effectiveness of non-copper alternatives. In addition to hazard assessment, Ecology lacks performance data to evaluate these alternatives and determine whether they are effective for use in Washington's waterways.

To address this data gap, we contracted with researchers from Washington State University to conduct performance testing. We compared the efficacy of copper-based, non-copper biocidal, and non-biocidal paints by testing up to 20 coating products on test panels at four sites in Puget Sound following a quality assurance project plan (Jamal et al., 2023). The test followed the Standard Test Method for Testing Antifouling Panels in Shallow Submergence, an American Society for Testing and Materials method (ASTM, 2020). This test mimics actual use of these paints. So rather than using aquatic species toxicity as a proxy for effectiveness, we directly measured the relative percentage of fouling coverage on painted panels in water. A static immersion test with coated panels is a worst-case scenario and represents the most demanding conditions for efficacy of antifouling paints.

We monitored and evaluated the overall fouling condition each month in this field study. We used the performance test to get better understanding of whether alternatives to copper-based paints are effective. A full presentation and discussion of the results from performance testing is in Appendix A.

Study design

Boat paint selection

Before the test started, Ecology reached out to boatyards and paint retailers for a survey. We asked for the most popular copper and non-copper paints used or sold in Washington, or any non-biocidal paints that they've heard of or were interested in. We selected 19 products based on surveys, pesticide registration data, and information from communication materials and internet forums. The final 19 products included ten non-copper biocidal paints, seven copper paints, and two non-biocidal paints.

Testing sites

We selected four test locations that are representative port areas in Puget Sound, including three saltwater site and one freshwater site. The freshwater site is closely connected to the marine environment. They either have heavy boat traffic or serve as a long-term boat moorage site. The four test locations are:

- Manchester Station, Port Orchard, WA (saltwater)
- Flounder Bay, Anacortes, WA (saltwater)
- Gig Harbor Station, Gig Harbor, WA (saltwater)

- Portage Bay, Seattle, WA (freshwater)

Test method

Following the standard ASTM method and manufacturer technical data sheets, the researchers used steel test panels with a size of 9x9 square inches, sandblasted them, and painted each panel with the required universal pretreatment coatings. Each panel was then painted with two to four coats of primers and two coats of a test antifouling product as the topcoat. In addition, we consulted manufacturing associates and painting professionals to achieve the best performance. For example, the researchers experimented and adjusted application pressures to make spray guns suitable for painting on smaller areas. In certain paints, they applied "tie and tack coats" suggested by manufacturer's instructions. In addition, the researchers performed standard adhesion and standard scratch tests on separate panels to inspect the bonding of the primers and topcoat for individual test products.

After the topcoat application, researchers submerged all test panels into the water at each location. The monitoring started in January 2023 and lasted for 12 months. Once per month, the researchers observed each panel individually, recorded the data, and reported the biofouling based on the test method. In addition to fouling monitoring, the researchers also recorded water physicochemical parameters such as temperature, salinity (conductivity), and pH.

At the end of the test, panels were gently washed with tap water to remove any loosely adhered sea mud, slime, or weed. This eliminated the beginning stages of fouling (especially algae) occurring on the panels.

The method defines a scoring system for qualitative data. The ASTM method specifically instructs reporting paint performance in four types of percent ratings on monthly basis:

- Fouling resistance rating
- Antifouling film rating
- Anticorrosive film rating
- Overall performance rating

The fouling resistance ratings evaluate the presence of fouling, including non-colonial forms such as barnacles and coelenterates in numbers and sizes, and colonial forms such as algae by percent surface covered. The antifouling and anticorrosive film ratings evaluate the physical conditions such as film defects from topcoat or primer (ASTM, 2020). To evaluate antifouling performance, fouling resistance ratings provide a better tool for comparison. The ratings scale from 0 to 100, where 100 represents no fouling presence.

Panel testing has its limitations since fouling occurs more readily on static surfaces. However, the static panel test is a good proxy to represent the worst-case scenarios and provides comparison under consistent conditions.

Final results

In this research study, we recorded the field parameters such as water temperature, dissolved oxygen (DO), pH, electrical conductivity (EC), and water hardness on each site before observing fouling. The research team visually inspected panels to determine fouling and took photographs for further analysis. At the end of the performance testing, each panel was gently washed with tap water or ocean water. Each paint was evaluated with the four types of percent ratings on a monthly basis. The data analysis focused on fouling resistance ratings, as well as monthly mean foul resistance ratings by month, and yearly mean foul resistance ratings by location.

Performance by types of paints

The seven copper-based paints contain cuprous oxide ranging from 25% to 47.5%. At the end of the test, many test panels have thin layers of biofilm or slime, receiving fouling resistance ratings from 18 to 68 in the last month (mean value in saltwater locations). Based on the monthly and yearly mean ratings, CUKOTE showed the best performance in foul resistance, followed by other top performers such as AF33.

The ten non-copper paints contain either Tralopyril, zinc pyrithione, DCOIT, or some combination of two of these ingredients. When grouped together, the ten non-copper paints didn’t show significantly different performance compared to the seven copper-based paints.

Several non-copper biocidal paints consistently performed well among separate locations. The fouling resistance ratings of non-copper biocidal paints ranged from 42 to 73 at saltwater locations in the last month. The top-performing paints include EPAINT EP-2000 and EP ZO, which both contained zinc pyrithione as the single biocide. Each tested paint may use one or two ingredients at different levels, so it’s hard to perform chemical to chemical comparison for the performance. Generally, we found the use of zinc pyrithione outperformed other ingredients and effectively prevented the test panels from fouling within the testing period.

Among the non-copper biocidal paints, SN-1 is the only product that uses DCOIT as a single biocide. However, this product cannot provide comparable performance among the 19 tested products. In the monthly mean ratings, SN-1 either received the lowest or second lowest ratings in six out of twelve months. In the yearly mean ratings by location, SN-1 received the lowest rating in Gig Harbor and was outperformed by other paints in Port Orchard and Anacortes.

During the market survey, we found only two non-biocidal paints in the market, and those are not used for recreational boats. These two products, InterSleek 1100SR and Propspeed, showed exceptional performance across four test locations. The ultra-smooth surface of InterSleek 1100SR resulted in outstanding performance in most locations.

Performance by time and locations

Paint performance can change over time, and the fouling resistance ratings can increase or decrease over the months. As a result, we provide both monthly and yearly average fouling resistance ratings for the test panels in Appendix A. Fouling growth on the panels increased significantly during the warmer months – March to September 2023. During these months, the water temperature and dissolved oxygen readings were also higher compared to what we recorded in colder months – November 2023 to January 2024. The fouling activity dropped and some of the beginning stages of algae was reduced on many panels in colder months, between November 2023 and January 2024.

The data analysis showed relatively strong positive correlation between the antifouling rating and the dissolved oxygen concentration. That is, as the dissolved oxygen concentration increases, the antifouling performance of the paints tends to increase. On the other hand, there is a relatively strong negative correlation between the antifouling rating and the water temperature. In a warm water body, the fouling growth on the panels increased significantly and the antifouling ratings dropped. Fouling growth can vary due to combined effects of temperature, pH and dissolved oxygen concentrations.

We observed that paint performance is heavily dependent on the test locations, even though they are all within Puget Sound area. All paints obtained better ratings in freshwater than in saltwater. The only product that uses DCOIT received a lower performance score compared to all other paints in three saltwater locations but worked well in freshwater location. Among the four test locations, Anacortes is the one location where the paints exhibited an overall lower performance.

Discussion

Some research has compared the efficacy of copper-based antifouling paints to newer technologies or products marketed as “eco-friendly” (Arboleda-Baena et al., 2023; Tsimnadi 2023). Those studies show that traditional copper antifouling paints work equally well or better than other options, including non-biocidal paints. With the copper leach rate limit in effect, there are concerns that paints with a lower copper content or lower leach rate won’t sufficiently prevent biofouling. The Biocidal Products Regulation in the European Union recommends that the dose of the biocidal product should be the minimum necessary to achieve the desired effect. Literature shows that commercial antifouling paints with lower leach rate can be equally efficient compared to products with high release rates (Lagerström et al., 2020).

Based on this performance test, we found popular copper-based, non-copper based, and non-biocidal paints all have satisfactory performance. The overall best performers, regardless of test location and time, are EP 2000 containing 4.70% zinc pyrithione, Propspeed® and Intersleek® 1100 SR that are non-biocidal, and CUKOTE and AF33 that contains cuprous oxide at 47.57% and 33.60%, respectively. However, the safer biocide, DCOIT, showed relatively low performance in all saltwater locations.

We recognize that there are limitations to this 12-month static panel testing. Compared to hydrodynamic panel testing, static panel testing can provide a baseline performance evaluation, but may underestimate those paints that perform better in motion. All the ratings are specific to the inspection time and location, which may not reflect their performance in other scenarios. This performance testing is not intended to endorse any products.

Conclusions

In 2020, the Washington Legislature directed Ecology to continue to collect and review information related to antifouling boat paints. Our review focused on relevant and credible scientific information that became available since 2019. As a follow up to two earlier reports, this study provides more evidence to show that current alternative paints and ingredients have either hazard concerns or data gaps regarding effectiveness.

In the continuous search for alternatives to copper, we consider reducing hazards and achieving desirable performance as the current top priorities. We provide definitions for safer, effective, feasible, reasonable, and readily available.

Ecology developed criteria and helped define "safer" for antifouling chemicals and assessed potential alternatives to copper in paints. When applying the criteria for what constitutes a safer alternative, chemicals should be less hazardous to non-target species, less persistent, and release fewer toxic chemicals into the environment. The criteria we used is based on the minimum requirements from Safer Products for Washington to identify safer alternatives. We then added special considerations on exposure magnitude and an additional data review to focus on non-target species.

In review of non-copper biocidal ingredients, only three chemicals—Tralopyril, zinc pyrithione and DCOIT—are registered to use in the United States and Washington. Our review on the hazard data shows that:

- Tralopyril turns into persistent chemicals after hydrolysis. It shows very high ecotoxicity and major risks to human health, including very high acute mammalian toxicity, single exposure neurotoxicity, and developmental toxicity.
- Zinc pyrithione is persistent in a marine environment. New information shows it's a chemical with high developmental toxicity in humans and may posing occupational health risks in boat painters.
- DCOIT exhibits high and non-selective toxicity to marine organisms. This emerging biocide, however, has low persistence and low bioaccumulation and can degrade rapidly in seawater.

Based on the criteria for safer antifouling chemicals, Tralopyril and zinc pyrithione don't pass the criteria to be safer. The currently available information show that DCOIT, with a score of GreenScreen® Benchmark-2 – Use but search for Safer Substitutes, passes the minimum criteria to be safer.

The review on effectiveness revealed significant data gaps in performance. New products are undertested. We cannot verify the credibility and relevance of performance data, particularly for DCOIT. To explore effectiveness evaluation, Ecology conducted a performance test on antifouling products. The 12-month test shows that that products based on DCOIT alone presented lower performance compared to non-copper biocidal paints. They also work less effectively than most copper paints in saltwater locations. Considering this is a single test, Ecology lacks sufficient and credible data to conclude that DCOIT is an effective antifoulant to replace copper in Washington.

In reviewing non-biocidal paints, we found that non-biocidal paints are primarily designed for commercial vessels, not recreational boats. Though some products for commercial vessels showed good performance, our review found that these emerging products have hazard concerns from use of PFAS. We found that studies discussing the environmental risks and toxicities of these paints and ingredients are not sufficient to conclude they are safer than copper-based antifouling paints.

Based on the review that focused on "safer and effective," Ecology is not able to determine "that safer and effective alternatives to copper-based antifouling paints are feasible, reasonable, and readily available" pursuant to RCW 70A.445.020 for the following reasons:

- Our review raises significant concerns on existing non-copper biocides. We have sufficient evidence to recognize Tralopyril and zinc pyrithione as chemicals that either persist in the environment, pose risks to human health or harm non-target aquatic species. Though DCOIT is safer due to rapid biodegradation, we lack credible and sufficient data to conclude its effectiveness in products.
- New biocides go through long pesticide registration and review process. We don't anticipate new biocides will likely become readily available in the near future.
- Non-biocides are under development. We lack sufficient data about the composition and possible releases from these new products.

As a result, the potential restrictions on copper-based paints in RCW 70A.445.020(3)(a)–(c) will not take effect and Ecology will conduct a second review of relevant studies and information. A follow-up report will be submitted to the Legislature by June 30, 2029.

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Appendix A: Performance Testing Results

by Mueed Jamal and Xianming Shi
Washington State University

Introduction

Over the past decade, the paint industry has developed new antifouling paint products, including non-copper alternatives, and marketed them as more environmentally friendly. However, Ecology currently lacks performance data to evaluate these alternatives and determine whether they are effective replacements for copper-based paints in Washington's waterways.

In this comparative study, researchers tested the efficacy of copper-based and copper-free antifouling paints in real waters around Puget Sound in Washington. The performance testing used a total of 19 antifouling paint systems and lasted for twelve months. Four test locations, Port Orchard, Gig Harbor, Seattle (west), and Anacortes, were used to submerge steel panels. Researchers monitored the test panels every month and presented the most relevant data from all 12 months in this Appendix. The study can develop understanding on how copper-based and copper-free antifouling paints performed in saltwater and freshwater.

A Quality Assurance Project Plan was published for this research study. The study objectives, as defined, are to test performance based on the ASTM standard method, and to adopt a comparative approach to evaluate performance of different paints (Ecology, 2023). The plan also included details such as project description, quality objectives, study design, field procedures, and data verification. This report is prepared in the light of the published quality assurance project plan and the available ASTM standard test method for testing antifouling panels in shallow submergence.

Materials and Methods

Antifouling paints

The antifouling paints used in this research study were either copper-based or copper-free. All of them, except two non-biocidal paints, contain active ingredients. Several of these are ablative (self-polishing) paints. Table 4 provides details on the characteristics of all the paints, including the control paint, PIN 19 SeaVoyage®. It also provides the panel identification number (PIN) used for each panel.

Table 4: Characteristics and nature of antifouling paints used in performance testing.

PIN	Paints	Ingredients	Biocidal	Ablative
1	Hydrocoat® ECO	6.0% Tralopyril; 4.80% zinc pyrithione	Yes	Yes
2	ECO HRT®	6.0% Tralopyril; 4.80% zinc pyrithione	Yes	No

PIN	Paints	Ingredients	Biocidal	Ablative
3	Micron CF	3.90% Tralopyril; 4.12% zinc pyrithione	Yes	Yes
4	Pacifica Plus	3.90% Tralopyril; 4.12% zinc pyrithione	Yes	Yes
5	Smart Solution	2.90% Tralopyril	Yes	Yes
6	Shelter Island Plus™	5.60% Tralopyril; 4.00% zinc pyrithione	Yes	Yes
7	EP-ZO	4.80% zinc pyrithione	Yes	Yes
8	SN-1	2.91% DCOIT	Yes	Yes
9	EP-2000	4.70% zinc pyrithione	Yes	No
10	Intersleek® 1100 SR	N/A	No	No
11	Propspeed®	N/A	No	No
12	CUKOTE	47.57% Cuprous Oxide	Yes	Yes
13	AF 33	33.60% Cuprous Oxide	Yes	Yes
14	Sharkskin™	45.20% Cuprous Oxide	Yes	No
15	PCA Gold	47.50% Cuprous Oxide	Yes	Yes
16	Micron® CSC*	37.20% Cuprous Oxide	Yes	Yes
17	Fiberglass Bottomkote® NT	25.00% Cuprous Oxide	Yes	Yes
18	Interspeed 640	41.97% Cuprous Oxide	Yes	Yes
19	SeaVoyage®	7.28% Tralopyril; 6.38% zinc pyrithione	Yes	Yes

Materials: Panels, racks, and ropes

Panels are A569 steel plates, 11 gauge, 0.12” thick, and 9x9 in² by size. They were sandblasted according to technical data sheets, prior to applying any paints. The exposed and painted area for each panel was 81 in².

The racks are made of marine-grade high-density polyethylene, either 4’ by 1’ or 2.2’ by 1’. The longer racks accommodated eight panels – four on each side. The smaller racks each had three panels, two on one side and one on the other.

The paints were applied on each panel by following the manufacturers’ instructions and were fully cured to no tacky state. The panels were mounted on racks using the non-conductive fiberglass studs and hex nuts to avoid corrosion. The racks were then submerged in water, only after the minimum period required before flooding was achieved and no later than the maximum time limit after the paint application. Prior to flooding, the thickness of the paint system was measured for each panel. Racks were submerged between 1.5 to 3.5 feet deep below water. Figure 2 shows the rack with a mounted panel (PIN 19, SeaVoyage®) before submerging into water.

Figure 2: A panel mounted on the rack before submerging into lake water in Seattle, WA.

Initially, the ropes used to tie the racks with the piers or rafts were polypropylene (yellow ropes in the Figure 2). However, they degraded quickly under the sunlight, and were replaced by ¼-inch thick Nylon 3-strand rope after a few months of monitoring, as shown in Figure 2. At the Seattle Yacht Club, additional cleats were also mounted to support the racks.

Method – ASTM D3623-78a

This research study followed the ASTM standard test method for evaluating antifouling paints in shallow submergence (ASTM, 2020) with minor deviations. For instance, the ASTM method only requires one test location, but we tested in four separate locations. Due to the total number of test panels and the limitation of maximum time before flooding, it was not possible to use replicates for each paint on each location. Rather than replicating panels in each location, we used multiple saltwater locations to test each paint. The freshwater location didn't employ replicates, rather we relied on the high level of consistency from paint application. The paints were mixed and prepared only once and were applied to all four panels for all four locations within a day.

The ASTM method instructs reporting in four types of percent ratings: fouling resistance (F.R.) rating, antifouling film (A.F.) rating, anticorrosive film (A.C.) rating, and overall performance (O.P.) rating. The fouling resistance rating is used to evaluate the presence of fouling on each panel. The antifouling film rating and the anticorrosive film rating are two physical condition parameters that represent level of defects for the topcoat and the primer, respectively. The lowest number of all three ratings is selected as the overall performance rating. In this study, all four ratings were allotted to each panel, every month, from all test locations.

To report the fouling resistance rating, each test panel surface was awarded a rating of 100 if no visible incipient or mature fouling was present. Biological slime (jelly-like slimy gray or clear mold), algal spores (mostly microscopic), sea mud from the ocean bed, oxidation, and salt marks or residue, did not contribute to the ratings. The rating was reduced to 95 if incipient fouling was present on the panel. If mature forms of fouling were present, the rating was subtracted with a sum from the number of individuals present for non-colonial fouling such as barnacles, and/or the percent area covered by colonial fouling, like algae, and encrusting bryozoans.

To report the antifouling film rating, a panel received a rating of 100 if no physical defects including chipping, blistering, discoloring, etc., were present on the antifouling paint, otherwise percent area affected by such defects was subtracted from 100. The rating criteria of anticorrosive film rating is similar to antifouling film rating, as both ratings focus on physical defects.

Among the four ratings, fouling resistance rating aligns well with the study objective to evaluate the paint performance against fouling and therefore becomes a better parameter for comparison. Thus, for targeted analysis, fouling resistance ratings are more emphasized and analyzed for each paint from every month. Moreover, we analyzed monthly mean fouling resistance ratings for saltwater locations only and the yearly mean fouling resistance ratings for all locations to compare different antifouling paint systems.

Often panels have incipient algae that was not easy to distinguish from sea mud or sea slime. Mature algae could be present underneath incipient algal slime. In such cases, a good approximation was made, and the benefit of the doubt was given to the paint during the study. At the end of the research study, the panels were gently washed with flowing tap water. To identify any loosely adhered or incipient fouling, videos were made before, and photographs were taken after the washing process. Washing also ensured that there were no loosely adhered marine contaminants including sea mud, soil, weed, and so forth, on the panels, before they were rated for antifouling performance at the end of year-long testing.

Additional information

The performance ratings for panels are specific to the evaluation time, test location, and tested products. It is worth noting that the fouling conditions can improve or worsen over time and some of the data may only represent the condition at that time. With continuous monitoring over 12 months, we collected a large amount of images and data. For example, all four percent ratings were obtained for each panel, every month, at all test locations. This produced a total of 46 tables for year-long testing. To keep this Appendix at a reasonable length, we only included the most relevant data needed for discussion.

Much of the data regarding ASTM fouling ratings for all the months, paint thickness measurements, and original photographs are moved to additional information. Additional information is available upon request through the antifouling boat paint webpage.[15]

[15] https://www.ezview.wa.gov/site/alias__1962/39937/antifouling_boat_paint.aspx

Results

Water tests

In this research study, we recorded the field parameters such as water temperature, dissolved oxygen (DO), pH, electrical conductivity (EC), and water hardness on each site before observing fouling. The results of water-based tests are shown in Table 5.

Table 5: Temperature, pH, conductivity, and DO of saltwater and freshwater at all test sites

Test Location	Temp. (° C)	DO (mg/L)	pH	*EC (mS/cm)	Hardness (ppm)
Port Orchard — February 2023	8.8	11	7.45	N/A	425+
Gig Harbor — February 2023	8.3	11.3	7.8	N/A	425+
Seattle — February 2023	7.8	13.1	8.1	0.09	45
Anacortes — February 2023	7.5	–	–	–	–
Port Orchard — March 2023	8.8	10.4	7.9	N/A	425+
Gig Harbor — March 2023	8.3	11.3	7.8	N/A	425+
Seattle — March 2023	7.9	12.6	8	0.08	50
Anacortes — March 2023	7.5	11.6	7.8	N/A	425+
Port Orchard — April 2023	10.3	10.1	7.9	N/A	425+
Gig Harbor— April 2023	12.1	11.3	8.1	N/A	425+
Seattle— April 2023	11.2	10.4	8	0.08	50
Anacortes — April 2023	10	10.4	7.9	N/A	425+
Port Orchard — May 2023	12.2	10.4	8	N/A	425+
Gig Harbor — May 2023	15.2	12.5	8.1	N/A	425+
Seattle — May 2023	21	10.8	8.8	0.08	50
Anacortes — May 2023	14.2	13.2	8.3	N/A	425+
Port Orchard — June 2023	14.8	11.5	7.8	N/A	425+
Gig Harbor — June 2023	18.3	13	8	N/A	425+
Seattle — June 2023	21.1	9.9	8.6	0.08	50
Anacortes — June 2023	14.7	11.4	8.2	N/A	425+
Port Orchard — July 2023	14.1	10.9	7.9	N/A	425+
Gig Harbor — July 2023	18.3	13.1	8.1	N/A	425+
Seattle — July 2023	25.5	17.6	10.2	0.09	60
Anacortes — July 2023	15.8	10.5	7.7	N/A	425+
Port Orchard — August 2023	13.9	9.2	7.6	N/A	425+

Test Location	Temp. (° C)	DO (mg/L)	pH	*EC (mS/cm)	Hardness (ppm)
Gig Harbor — August 2023	17	12.5	7.8	N/A	425+
Seattle — August 2023	22.2	9.7	8.8	0.09	50
Anacortes — August 2023	14.1	9.1	7.7	N/A	425+
Port Orchard — September 2023	13.6	7.6	7.8	N/A	425+
Gig Harbor — September 2023	15	8.8	7.7	N/A	425+
Seattle — September 2023	16.7	9.1	8.8	0.07	40
Anacortes — September 2023	12.1	11.1	7.9	N/A	425+
Port Orchard — October 2023	12.6	8.5	7.5	N/A	425+
Gig Harbor — October 2023	12.2	7.9	7.5	N/A	425+
Seattle — October 2023	12.9	10.1	8.5	0.07	N/A
Anacortes - October 2023	10	8.9	7.7	N/A	425+
Port Orchard — November 2023	11.1	8.5	7.5	N/A	425+
Gig Harbor — November 2023	10.5	8.1	7.6	N/A	425+
Seattle — November 2023	8.7	10.9	8.6	0.06	40
Anacortes — November 2023	9.4	8.6	7.8	N/A	425+
Port Orchard — December 2023	10.5	7.2	7.4	N/A	425+
Gig Harbor — December 2023	10.5	4.4	7.3	N/A	425+
Seattle - December 2023	7.9	8.5	8.3	0.07	50
Anacortes- December 2023	9.1	9.1	7.7	N/A	425+
Port Orchard - January 2024	9.7	9.5	7.3	N/A	425+
Gig Harbor - January 2024	9.7	9.5	7.2	N/A	425+
Seattle - January 2024	7.8	10.5	7.7	0.07	50
Anacortes - January 2024	8.6	9.6	7	N/A	425+

Table notes:

- For February and March 2023, the water temperatures are recorded from an online source (weatherspark.com, wrcc.dri.edu).

Due to excessive water turbulence from ferry engine turbines at the original Anacortes test site, we had to bring the panels back to WSU Pullman campus for touching and re-painting. We then submerged them at a new nearby test site in Anacortes in March 2023. So, for Anacortes, we presented data from 10 months of performance testing.

Visual examination of test panels

Panels were physically observed each month to determine fouling, and their photographs were inspected. Some of the typical marine fouling types found in the Puget Sound include barnacles, coelenterates, encrusting bryozoans, hydroids, tunicates, filamentous bryozoans, and algae. The performance testing generated a total of 912 images with 76 from each month. Here we only include the photographs of panels after gentle washing, from January 2024, the last month of study.

Panels after gentle washing

At the end of the performance testing, each panel was gently washed with tap water except at Anacortes, where ocean water was used in a pitcher. We recorded panel conditions before and after the gentle washing, in the form of photos and videos. Figures 3 to 21 show the panels' conditions from January 2024 in all four test locations, after the gentle washing.

Figure 3: SeaVoyage® (control), PIN 19 – from Port Orchard, Gig Harbor, Anacortes, and Seattle – January 2024 (left to right).

Figure 4: Hydrocoat® ECO, PIN 1 – from Port Orchard, Gig Harbor, Anacortes, and Seattle – January 2024 (left to right).

Figure 5: ECO-HRT®, PIN 2 – from Port Orchard, Gig Harbor, Anacortes, and Seattle – January 2024 (left to right).

Figure 6: Micron CF, PIN 3– from Port Orchard, Gig Harbor, Anacortes, and Seattle – January 2024 (left to right).

Figure 7: Pacifica Plus, PIN 4 – from Port Orchard, Gig Harbor, Anacortes, and Seattle – January 2024 (left to right).

Figure 8: Smart Solution, PIN 5 – from Port Orchard, Gig Harbor, Anacortes, and Seattle – January 2024 (left to right).

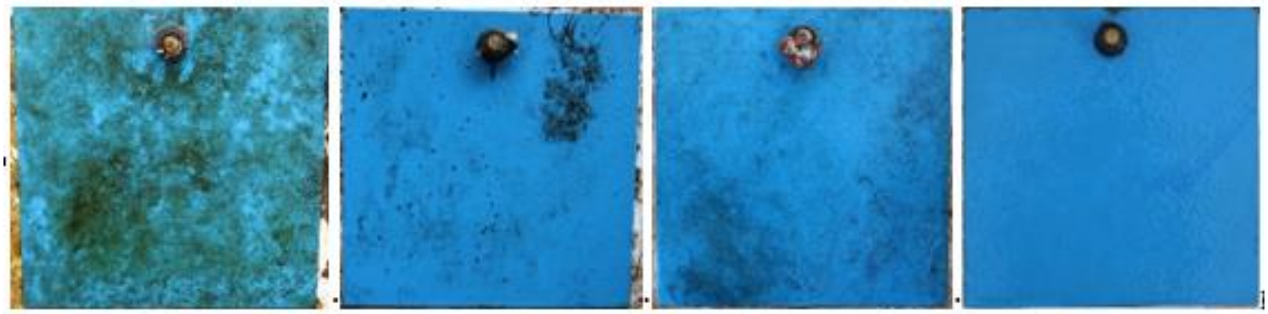

Figure 9: Shelter Island Plus™, PIN 6 – from Port Orchard, Gig Harbor, Anacortes, and Seattle – January 2024 (left to right).

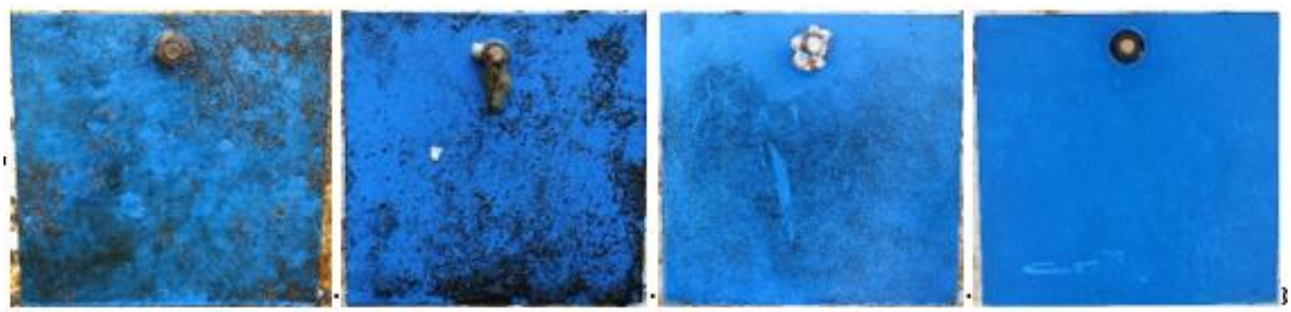

Figure 10: EP-ZO, PIN 7 – from Port Orchard, Gig Harbor, Anacortes, and Seattle – January 2024 (left to right).

Figure 11: SN-1, PIN 8 – from Port Orchard, Gig Harbor, Anacortes, and Seattle – January 2024 (left to right).

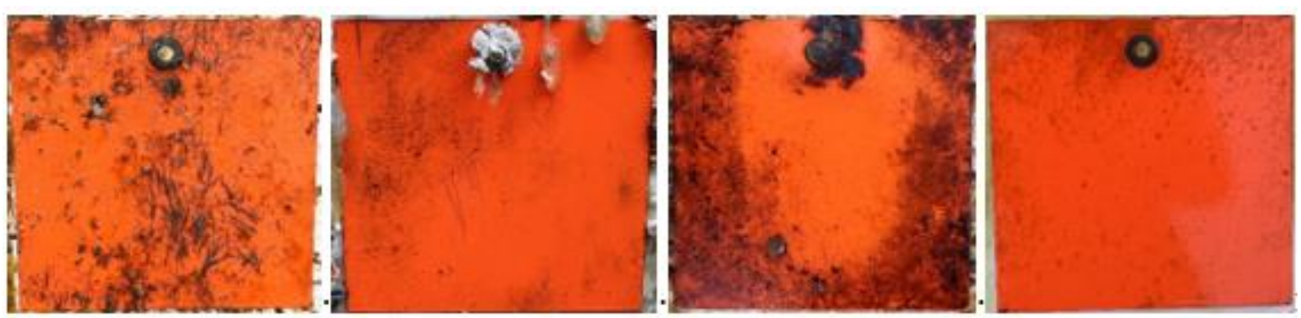

Figure 12: EP-2000, PIN 9 – from Port Orchard, Gig Harbor, Anacortes, and Seattle – January 2024 (left to right).

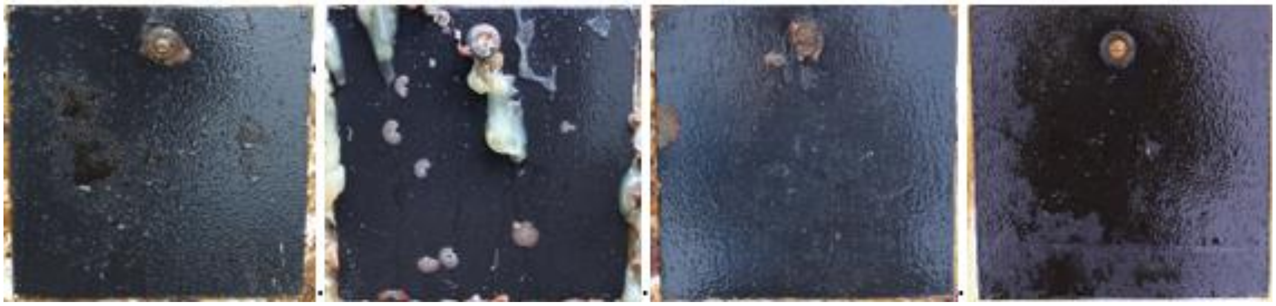

Figure 13: Intersleek® 1100 SR, PIN 10 – from Port Orchard, Gig Harbor, Anacortes, and Seattle – January 2024 (left to right).

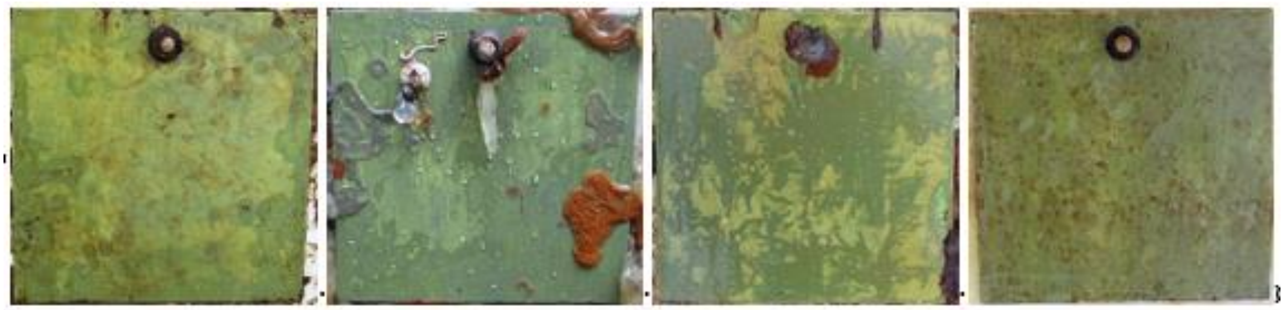

Figure 14: Propspeed®, PIN 11 – from Port Orchard, Gig Harbor, Anacortes, and Seattle – January 2024 (left to right).

Figure 15: CUKOTE, PIN 12 – from Port Orchard, Gig Harbor, Anacortes, and Seattle – January 2024 (left to right).

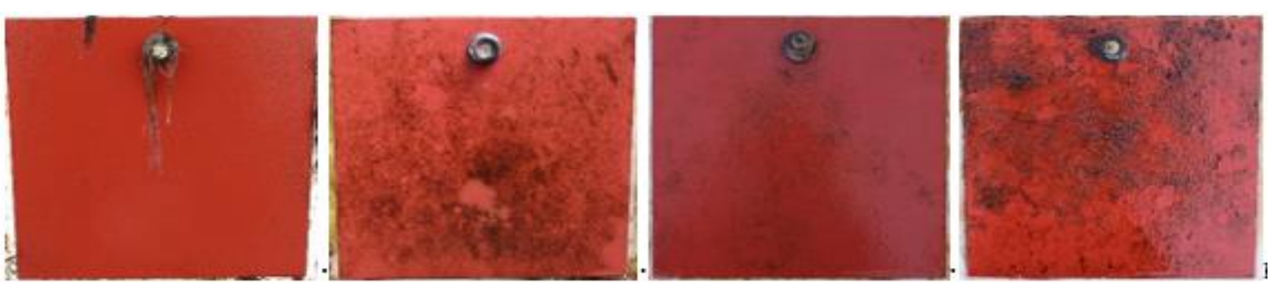

Figure 16: AF 33, PIN 13 – from Port Orchard, Gig Harbor, Anacortes, and Seattle – January 2024 (left to right).

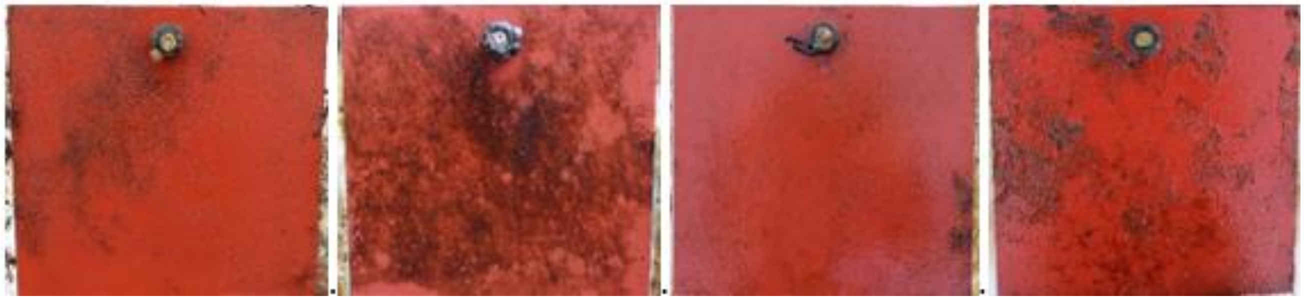

Figure 17: Sharkskin™, PIN 14 -- from Port Orchard, Gig Harbor, Anacortes, and Seattle – January 2024 (left to right).

Figure 18: PCA Gold, PIN 15 -- from Port Orchard, Gig Harbor, Anacortes, and Seattle – January 2024 (left to right).

Figure 19: Micron® CSC*, PIN 16 -- from Port Orchard, Gig Harbor, Anacortes, and Seattle – January 2024 (left to right).

Figure 20: Fiberglass Bottomkote® NT, PIN 17 – from Port Orchard, Gig Harbor, Anacortes, and Seattle – January 2024 (left to right).

Figure 21: Interspeed 640, PIN 18 -- from Port Orchard, Gig Harbor, Anacortes, and Seattle – January 2024 (left to right).

Image enhancement

In addition to visual inspection at the piers, the researchers observed photographs and edited the images using the right contrast, saturation, and brightness balance. Many photographs were also observed through advanced image editing tools like Windows Photos app, Adobe Photoshop, and Image J.

The examination followed non-destructive image testing techniques to avoid using artificial colors or forcefully adding a specific color intensity to the images. The temperature (or warm) setting was used with caution to avoid excessively increasing the green color intensity on the panels, which could have been misleading in understanding the percent amount of algae present. The tint option in editing was never used for any image editing.

Reflections in photographs from nearby surfaces with algae or green tone were carefully neglected. In the early months of testing (February to April 2023), oxidation is evident on many panels. The oxidation created a white layer on the paints, but the presence was not considered as fouling or contributed towards fouling resistance rating. Similarly, salt residues on paints were also not reported as fouling or physical defects. The standard method doesn't specify oxidation and salt residues, however, if present on the paints it may affect the functioning of antifouling paints.

Of all the 912 photographs, about 90% of them were edited to understand the growth of algae and to distinguish between the incipient and mature forms of fouling. Most of these edits were either done in the Windows Photos app or Photoshop by Adobe Inc. However, in rare cases, some photos were also edited using Image J. For instance, a photograph of the panel (PIN 9, EP 2000) from September 2023 at the Seattle location, was edited three times to confirm the right amount of algae present on it, as shown in Figure 22.

Similarly, a photograph of a panel (PIN 3, Micron CF) from Gig Harbor in August 2023 was edited both in the Windows app with high contrast, saturation, and warm settings while keeping the right white balance and was also edited in Photoshop, as shown in Figure 23.

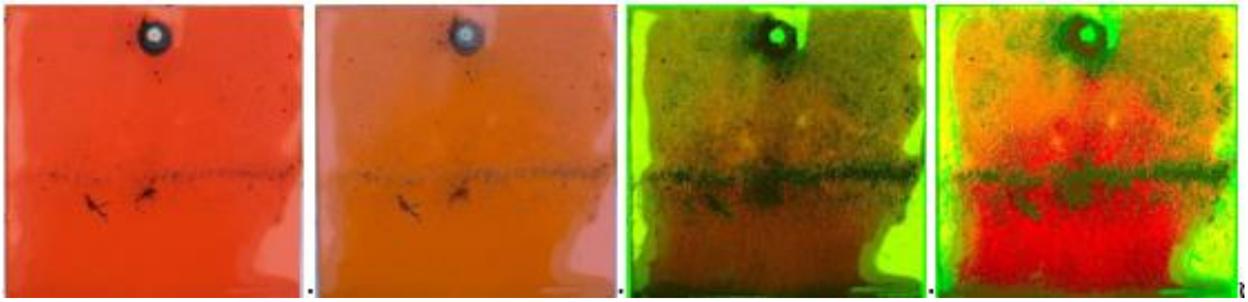

Figure 22: EP 2000, PIN 9 (Seattle, Sep 2023) – Original photograph (9a), edited in Windows Photos app (9b), edited with Image J (9c), further edited 9c in Image J (9d), to understand the right amount of algae growth.

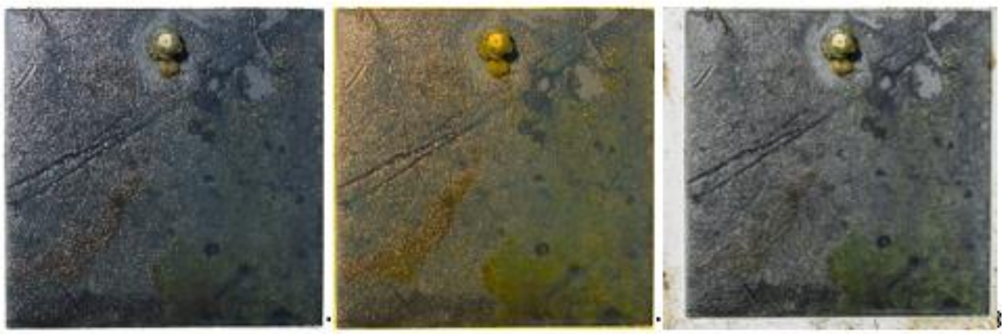

Figure 23: Micron CF, PIN 3 (Gig Harbor, Aug 2023) – Original photograph (3a), edited in Windows Photos app with high warm setting (1b), and edited with PS using camera raw filter with temp setting of 5 only (1c), to confirm the form of algae accumulation.

A photograph of a panel (PIN 8, EP SN-1) from Seattle in June 2023 showed almost no signs of algae growth. When it was rightly edited, the algae accumulation was more visible as shown in Figure 24. Often there were reflections on the panels due to water or other green objects from surroundings. This doubt was dealt with field observation, image enhancement and careful examination on the photos.

Because this study was done in static water, it was important to accurately quantify the loosely adhered incipient algae, particularly in freshwater where water movement was minimal. The benefit of the doubt was mostly given to the paints (particularly black-colored), limiting the area covered by mature algae up to a maximum of 65% on panels almost fully covered with algal slime. One such example is shown in Figure 25.

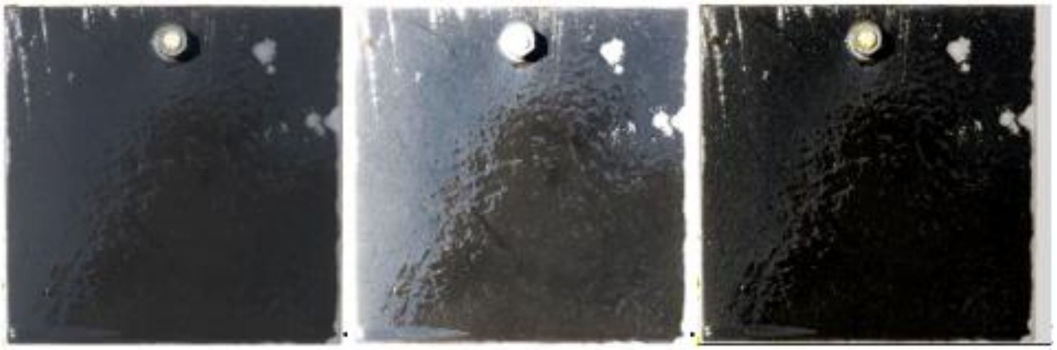

Figure 24: EP SN-1, PIN 8 (Seattle, June 2023) – Original photograph (8a), edited in Windows Photos app (8b), and edited with Photoshop using camera raw filter with temp setting of 10 only (8c), to confirm the algae accumulation underneath the slime.

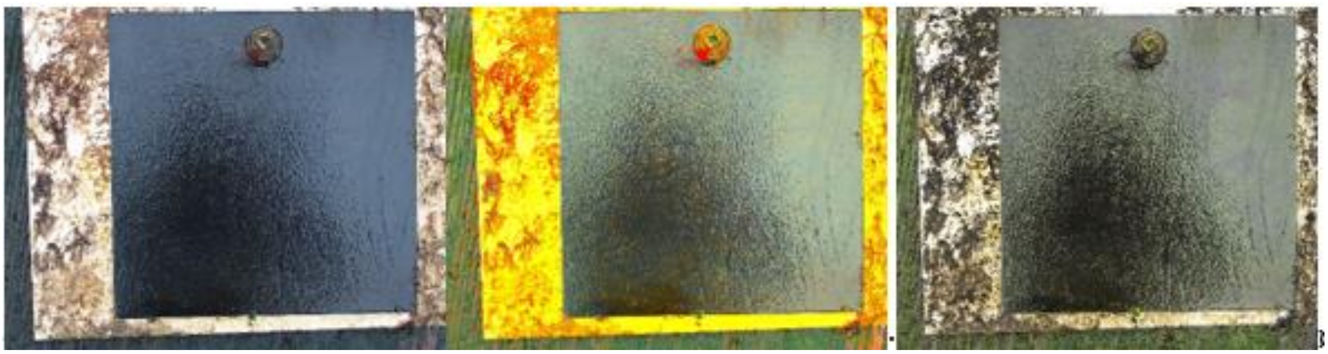

Figure 25: Hydrocoat® ECO, PIN 1 (Port Orchard, Dec 2023) – Original photograph (1a), edited in Windows Photos app with high warm setting (1b), and edited with PHOTOSHOP using camera raw filter (1c), to confirm the form of algae accumulation.

ASTM antifouling performance evaluation

To evaluate the performance of each antifouling paint, all four percent ratings were allotted to each panel, every month, at all test locations. The four types of percent ratings are: fouling resistance (F.R.) rating, antifouling film (A.F.) rating, anticorrosive film (A.C.) rating, and overall performance (O.P.) rating. To keep this Appendix reasonably short, we only included four rating tables from January 2024. Tables 6 to 9 show the four types of percent ratings of all paints from Port Orchard, Gig Harbor, Anacortes, and Seattle, respectively. These ratings are from January 2024 when researchers conducted panel inspection after gentle washing.

As mentioned above, fouling resistance rating, among the four types of ratings, provides a better tool to differentiate performance among the paints. In Tables 10 to 13, we list the fouling resistance ratings for all paints by month.

Table 6: ASTM all percent ratings for all paints at the end of January 2024 — Port Orchard, WA.

Origin: Ecology & WSU
Series: Performance Test
Base: Steel
Size: 9 inches x 9 inches

Place of immersion: Port Orchard, WA
Depth of immersion: 2.0 to 3.5 feet
Date immersed: January 21, 2023
Date inspected: January 2024

Test Surface PIN	Test Surface Paint	Mature Fouling on Surfaces	Incipient Fouling on Surfaces	Physical Condition	% Rating F.R.	% Rating A.F.	% Rating A.C.	% Rating O.P.
19	SeaVoyage ®	Algae (40%)	None	Clear	60	100	100	60
1	Hydrocoat® ECO	Algae (65%)	None	Clear	35	100	100	35
2	ECO HRT®	Algae (85%)	None	Clear	15	100	100	15
3	Micron CF	Algae (82%)	None	Clear	18	100	100	18
4	Pacifia Plus	Algae (80%)	None	Clear	20	100	100	20
5	Smart Solution	Algae (80%)	None	Clear	20	100	100	20
6	Shelter Island PlusTM	Algae (75%)	None	Clear	75	100	100	75
7	EP-ZO	Algae (75%) + Hyd (10%)	None	Clear	15	100	100	15
8	SN-1	Algae (95%)	(Barn)	Clear	90	100	100	90
9	EP-2000	Algae (12%) + Hyd (15%)	(Barn)	Blistering (topcoat) 5%	68	95	100	68

Test Surface PIN	Test Surface Paint	Mature Fouling on Surfaces	Incipient Fouling on Surfaces	Physical Condition	% Rating F.R.	% Rating A.F.	% Rating A.C.	% Rating O.P.
10	Intersleek® 1100 SR	Algae (10%)	None	Mud	90	100	100	90
11	Propspeed ®	Algae (8%)	None	Clear	92	100	100	92
12	CUKOTE	Algae (60%)	None	Clear	40	100	100	40
13	AF 33	Algae (5%)	None	Clear	95	100	100	95
14	SharkskinTM	Algae (20%)	None	Clear	80	100	100	80
15	PCA Gold	20% Algae	None	Chipping & Blistering (25%)	80	75	100	80
16	Micron® CSC*	Algae (15%)	None	Clear	85	100	100	85
17	Fiberglass Bottomkote ® NT	Algae (65%)	None	Clear	35	100	100	35
18	Interspeed 640	Algae (90%)	None	Clear	10	100	100	10

Abbreviations:

- Barn: Barnacles
- Hyd: Hydroids

Table 7: ASTM all percent ratings for all paints at the end of January 2023 — Gig Harbor, WA.

Origin: Ecology & WSU
Series: Performance Test
Base: Steel
Size: 9 inches x 9 inches

Place of immersion: Gig Harbor, WA
Depth of immersion: 1.5 to 3.5 feet
Date immersed: January 21, 2023
Date inspected: January 2024

Test Surface PIN	Test Surface Paint	Mature Fouling on Surfaces	Incipient Fouling on Surfaces	Physical Condition	% Rating F.R.	% Rating A.F.	% Rating A.C.	% Rating O.P.
19	SeaVoyage®	5% Algae	None	Clear	95	100	100	95
1	Hydrocoat® ECO	70% Algae	None	Clear	30	100	100	30
2	ECO HRT®	20% Algae	None	Chipping (topcoat) 2%	80	98	100	80
3	Micron CF	40% Algae	None	Chipping (topcoat) 2%	60	98	100	60
4	Pacifia Plus	20% Algae	None	Chipping (topcoat) 1%	80	99	100	80
5	Smart Solution	35% Algae + Barn (1)	None	Clear	64	100	100	64
6	Shelter Island PlusTM	25% Algae	None	Clear	75	100	100	75
7	EP-ZO	35% Algae	None	Clear	65	100	100	65
8	SN-1	85% Algae	None	Clear	15	100	100	15
9	EP-2000	15% v + Hyd 5%	None	Clear	80	100	100	80

Test Surface PIN	Test Surface Paint	Mature Fouling on Surfaces	Incipient Fouling on Surfaces	Physical Condition	% Rating F.R.	% Rating A.F.	% Rating A.C.	% Rating O.P.
10	Intersleek® 1100 SR	E.B (9%)	None	Clear	91	98	100	91
11	Propspeed®	E.B 20% + Barn (1)	None	Clear	79	100	100	79
12	CUKOTE	5% Algae	None	Clear	95	100	100	95
13	AF 33	65% Algae	None	Clear	35	100	100	35
14	SharkskinTM	80% Algae	None	Clear	20	100	100	20
15	PCA Gold	Algae (50%) + Barn (8)	None	Chipping & Blistering (topcoat) 25%	42	75	100	42
16	Micron® CSC*	70% Algae	Clear	None	30	100	100	30
17	Fiberglass Bottomkote® NT	68% Algae	None	Clear	32	100	100	32
18	Interspeed 640	67% Algae	None	Clear	33	100	100	33

Abbreviations:

- Barn: Barnacles
- E.B: Encrusting Bryozoans
- Hyd: Hydroids

Table 8: ASTM all percent ratings for all paints at the end of January 2024 — Anacortes, WA.

Origin: Ecology & WSU
Series: Performance Test
Base: Steel
Size: 9 inches x 9 inches

Place of immersion: Anacortes, WA
Depth of immersion: 2.5 to 3.5 feet
Date immersed: March 21, 2023
Date inspected: January 2024

Test Surface PIN	Test Surface Paint	Mature Fouling on Surfaces	Incipient Fouling on Surfaces	Physical Condition	% Rating F.R.	% Rating A.F.	% Rating A.C.	% Rating O.P.
19	SeaVoyage®	Algae (35%)	None	Clear	65	100	100	65
1	Hydrocoat® ECO	30% Algae	None	Chipping (topcoat) 5%	70	95	100	70
2	ECO HRT®	50% Algae	None	Chipping (topcoat) 5%	50	95	100	50
3	Micron CF	70% Algae	None	Chipping (topcoat) 3%	30	100	100	40
4	Pacifia Plus	75% Algae	None	Chipping (topcoat) 3%	25	97	100	25
5	Smart Solution	55% Algae	None	Chipping (topcoat) 3%	45	97	100	45
6	Shelter Island PlusTM	50% Algae	None	Clear	50	100	100	50
7	EP-ZO	50% Algae	None	Chipping (topcoat) 2%	50	100	100	50

Test Surface PIN	Test Surface Paint	Mature Fouling on Surfaces	Incipient Fouling on Surfaces	Physical Condition	% Rating F.R.	% Rating A.F.	% Rating A.C.	% Rating O.P.
8	SN-1	Algae (40%)	None	Chipping (topcoat) 5%	60	95	100	60
9	EP-2000	Algae (60%) + Barn (2)	None	Clear	38	100	100	38
10	Intersleek® 1100 SR	E.B (4%)	None	Chipping (topcoat) 4%	96	96	100	96
11	Propspeed®	None	None	Clear	100	100	100	100
12	CUKOTE	Algae (30%)	None	Clear	70	100	100	70
13	AF 33	Algae (25%)	None	Chipping (topcoat) 2%	75	98	100	75
14	SharkskinTM	Algae (40%)	None	Clear	60	100	100	60
15	PCA Gold	Algae (30%)	None	Chipping (topcoat) 30%	70	70	100	70
16	Micron® CSC*	Algae (45%)	None	Clear	55	100	100	55
17	Fiberglass Bottomkote® NT	Algae (65%)	None	Clear	35	100	100	35
18	Interspeed 640	Algae (90%)	None	Clear	10	100	100	10

Abbreviations:

- Barn: Barnacles
- E.B: Encrusting Bryozoans

Table 9**:** ASTM all percent ratings for all paints at the end of January 2024 — Seattle, WA.

Origin: Ecology & WSU
Series: Performance Test
Base: Steel
Size: 9 inches x 9 inches

Place of immersion: Seattle, WA
Depth of immersion: 1.5 to 3.5 feet
Date immersed: January 22, 2023
Date inspected: January 2024

Test Surface PIN	Test Surface Paint	Mature Fouling on Surfaces	Incipient Fouling on Surfaces	Physical Condition	% Rating F.R.	% Rating A.F.	% Rating A.C.	% Rating O.P.
19	SeaVoyage®	Low form algae (5%)	None	Clear	95	100	100	95
1	Hydrocoat® ECO	Algae (70%)	None	Clear	30	100	100	30
2	ECO HRT®	Algae (25%)	None	Clear	75	100	100	75
3	Micron CF	Algae (25%)	None	Clear	75	100	100	75
4	Pacifia Plus	Algae (15%)	None	Clear	85	100	100	85
5	Smart Solution	Algae (5%)	None	Clear	95	99	100	95
6	Shelter Island PlusTM	Algae (1%)	None	Clear	99	100	100	99
7	EP-ZO	None	None	Clear	100	100	100	100
8	SN-1	None	None	Clear	100	100	100	100

Test Surface PIN	Test Surface Paint	Mature Fouling on Surfaces	Incipient Fouling on Surfaces	Physical Condition	% Rating F.R.	% Rating A.F.	% Rating A.C.	% Rating O.P.
9	EP-2000	Algae (10%)	None	Clear	90	100	100	90
10	Intersleek® 1100 SR	Algae (30%)	None	Clear	70	100	100	70
11	Propspeed®	Algae (20%)	None	Clear	80	100	100	80
12	CUKOTE	Algae (35%)	None	Clear	65	100	100	65
13	AF 33	Algae (20%)	Barn, algae (40%)	Chipping (topcoat) 2 %	75	98	100	75
14	SharkskinTM	Algae (25%)	Barn, algae (35%)	Chipping (topcoat) 3%	70	97	100	70
15	PCA Gold	Algae (20%)	Barn, algae (25%)	Chipping (topcoat) 1%	75	99	100	75
16	Micron® CSC*	Algae (25%)	Barn, algae (30%)	Chipping (topcoat) 2%	70	98	100	70
17	Fiberglass Bottomkote® NT	Algae (4%)	None	Clear	96	100	100	96
18	Interspeed 640	Algae (80%)	None	Clear	20	100	100	20

Abbreviation:

- Barn: Barnacles

Table 10: Fouling resistance ratings by month for tested paint systems at Port Orchard saltwater site.

PIN	Feb. 2023	Mar. 2023	Apr. 2023	May 2023	Jun. 2023	Jul. 2023	Aug. 2023	Sep. 2023	Oct. 2023	Nov. 2023	Dec. 2023	Jan. 2024
19 (control)	100	100	85	70	70	70	50	50	45	45	55	60
1	87	55	35	92	92	85	25	25	35	30	35	35
2	95	55	35	93	98	65	30	25	45	30	35	15
3	95	55	30	85	75	65	30	25	50	30	45	18
4	95	30	30	90	79	80	25	20	50	30	50	20
5	93	80	35	75	65	60	42	25	45	45	50	20
6	93	94	90	80	70	80	60	50	50	57	50	75
7	93	96	97	97	70	85	53	90	35	70	47	15
8	85	92	60	35	45	24	27	54	85	89	30	90
9	99	97	99	85	91	80	63	64	65	73	55	68
10	60	100	90	98	98	98	60	100	95	95	60	90
11	92	75	97	93	90	79	90	99	87	90	73	92
12	96	80	85	75	93	60	92	98	95	98	85	40
13	94	90	88	45	75	50	35	50	50	75	87	95
14	99	90	80	30	55	98	40	20	50	55	70	80
15	100	90	90	60	90	96	30	65	45	55	65	80
16	99	90	90	25	80	87	35	20	35	55	87	85
17	99	95	75	93	62	77	45	15	75	90	55	35
18	75	90	25	89	85	62	30	10	30	90	45	10

Table 11**:** Fouling resistance ratings by month for tested paint systems at Gig Harbor saltwater site.

PIN	Feb. 2023	Mar. 2023	Apr. 2023	May 2023	Jun. 2023	Jul. 2023	Aug. 2023	Sep. 2023	Oct. 2023	Nov. 2023	Dec. 2023	Jan. 2024
19 (control)	100	100	99.5	93	93	55	30	35	25	63	95	95
1	100	100	98	100	98	55	85	70	35	30	35	30
2	100	100	99	100	58	55	92	65	30	30	45	80
3	100	100	100	80	60	40	75	40	30	30	50	60
4	100	100	98	99	45	40	45	35	25	30	65	80
5	98	60	55	65	70	40	65	10	50	30	45	64
6	100	95	35	50	40	60	30	45	30	30	55	75
7	100	100	99	56	85	72	45	45	55	50	65	65
8	90	100	2	25	45	45	15	35	30	30	25	15
9	100	100	100	98	99	100	70	70	71	65	77	80
10	98	90	55	27	100	50	45	10	12	75	89	91
11	100	22	35	33	79	69	50	8	14	62	90	79
12	100	99	45	50	70	70	75	55	55	50	90	95
13	100	100	100	100	60	65	75	65	55	70	85	35
14	100	100	100	100	60	65	55	55	55	65	65	20
15	100	100	100	100	55	70	55	45	27	45	40	42
16	100	100	100	100	55	65	55	50	15	45	50	30
17	98	100	99	94	55	55	55	40	35	45	30	32
18	90	98	80	94	45	40	45	15	30	95	30	33

Table 12: Fouling resistance ratings by month for tested paint systems at Anacortes saltwater site.

PIN	Feb. 2023	Mar. 2023	Apr. 2023	May 2023	Jun. 2023	Jul. 2023	Aug. 2023	Sep. 2023	Oct. 2023	Nov. 2023	Dec. 2023	Jan. 2024
19 (control)	N/A	N/A	99	96	60	52	45	40	45	40	55	65
1	N/A	N/A	90	70	50	90	40	20	50	15	50	70
2	N/A	N/A	85	95	30	82	55	25	25	15	40	50
3	N/A	N/A	60	97	50	70	30	20	20	15	40	30
4	N/A	N/A	70	80	50	75	50	25	20	10	35	25
5	N/A	N/A	90	90	80	55	30	23	19	30	30	45
6	N/A	N/A	99	90	90	59	40	25	10	30	35	50
7	N/A	N/A	99	94	99	55	45	35	25	45	50	50
8	N/A	N/A	100	98	95	40	61	35	15	40	45	60
9	N/A	N/A	100	100	99	44	73	56	49	49	54	38
10	N/A	N/A	100	92	80	40	58	23	42	54	60	96
11	N/A	N/A	85	35	35	86	91	96	75	90	97	100
12	N/A	N/A	94	57	45	65	55	55	35	55	55	70
13	N/A	N/A	24	50	55	50	40	50	75	60	70	75
14	N/A	N/A	92	50	60	50	30	55	65	55	65	60
15	N/A	N/A	96	50	65	50	25	40	25	50	50	70
16	N/A	N/A	95	50	55	50	30	35	30	55	55	55
17	N/A	N/A	98	55	55	50	30	40	30	45	35	35
18	N/A	N/A	88	35	30	45	25	20	10	35	30	10

Table 13**:** Fouling resistance ratings by month for all tested paint systems at the freshwater site, Seattle WA.

PIN	Feb. 2023	Mar. 2023	Apr. 2023	May 2023	Jun. 2023	Jul. 2023	Aug. 2023	Sep. 2023	Oct. 2023	Nov. 2023	Dec. 2023	Jan. 2024
19 (control)	100	99.5	99	87	90	95	90	50	80	60	65	95
1	100	100	90	100	90	80	40	55	35	55	55	30
2	100	98	70	98	55	80	40	35	35	45	45	75
3	100	98	30	75	85	85	70	30	100	45	55	75
4	100	100	45	75	85	85	70	45	35	45	55	85
5	92	85	87	75	90	95	75	65	91	70	87	95
6	94	75	89	60	90	95	90	40	60	40	40	99
7	99	94	80	50	65	80	65	40	45	50	55	100
8	100	92	92	75	65	100	98	65	100	75	95	100
9	100	100	100	92	92	98	92	45	65	50	98	90
10	100	94	45	45	60	99	99	99	100	95	96	70
11	95	91	83	25	75	82	99	75	85	98	99	80
12	95	98	90	85	75	94	85	65	60	50	75	65
13	92	90	75	85	80	93	83	65	35	55	55	75
14	92	88	80	85	85	93	83	65	35	55	50	70
15	92	88	80	85	77	94	83	65	35	60	50	75
16	91	90	75	85	88	90	85	55	45	55	50	70
17	92	95	87	65	88	90	87	85	65	55	55	96
18	95	100	55	50	70	95	75	30	38	40	40	20

Paint performances at saltwater sites

To better compare different paints, monthly mean saltwater fouling resistance rating for each paint is determined by averaging the values from all three saltwater locations. These monthly mean saltwater fouling resistance ratings are reported in Table 14. For February and March 2023, the monthly mean ratings were calculated using data from Port Orchard and Gig Harbor sites only.

Table 14: Monthly mean fouling resistance (F.R.) percent ratings for all saltwater locations each month.

PIN	Feb. 2023	Mar. 2023	Apr. 2023	May 2023	Jun. 2023	Jul. 2023	Aug. 2023	Sep. 2023	Oct. 2023	Nov. 2023	Dec. 2023	Jan. 2024
19	100*	100*	74.3	86.3	74.3	59.0	41.7	41.7	38.3	49.3	68.3	73.3*
1	93.5	77.5	74.3	87.3	80.0	76.7*	50.0	38.3	40.0	25.0	40.0	45.0
2	97.5	77.5	73.0	96*	62.0	67.3	59.0	38.3	33.3	25.0	40.0	48.3
3	97.5	77.5	63.3	87.3	61.7	58.3	45.0	28.3	33.3	25.0	45.0	36.0
4	97.5	65	66.0	89.7*	58.0	65.0	40.0	26.7	31.7	23.3	50.0	41.7
5	95.5	70	60.0	76.7	71.7	51.7	45.7	19.3	38.0	35.0	41.7	43.0
6	96.5	94.5	74.7	73.3	66.7	66.3	43.3	40.0	30.0	39.0	46.7	66.7
7	96.5	98*	98.3*	82.3	84.7*	70.7	47.7	56.7	38.3	55.0	54.0	43.3
8	87.5	96	54.0	52.7	61.7	36.3	34.3	41.3	43.3	53.0	33.3	55.0
9	99.5*	98.5*	99.7*	94.3*	96.3*	74.7*	68.7*	63.3*	61.7*	62.3	62.0	62.0
10	79	95	81.7	72.3	92.7*	62.7	54.3	44.3	49.7	74.7*	69.7	92.3*
11	96	48.5	72.3	53.7	68.0	78*	77*	67.7*	58.7	80.7*	86.7*	90.3*
12	98	89.5	74.7	60.7	69.3	65.0	74*	69.3*	61.7*	67.7	76.7*	68.3
13	97	95	70.7	65.0	63.3	55.0	50.0	55.0	60*	68.3	80.7*	68.3
14	99.5*	95	90.7	60.0	58.3	71.0	41.7	43.3	56.7	58.3*	66.7	53.3
15	100*	95	95.3*	70.0	70.0	72.0	36.7	50.0	32.3	50.0	51.7	64.0
16	99.5*	95	95*	58.3	63.3	67.3	40.0	35.0	26.7	51.7	64.0	56.7

PIN	Feb. 2023	Mar. 2023	Apr. 2023	May 2023	Jun. 2023	Jul. 2023	Aug. 2023	Sep. 2023	Oct. 2023	Nov. 2023	Dec. 2023	Jan. 2024
17	98.5	97.5*	90.7	80.7	57.3	60.7	43.3	31.7	46.7	60.0	40.0	34.0
18	82.5	94	64.3	72.7	53.3	49.0	33.3	15.0	23.3	73.3	35.0	17.7

*These values show the top 20% of the paints for each month.

Table 14 highlights the top 20% ratings each month based on the monthly mean fouling resistance ratings. Based on the top ratings, EP 2000 (PIN 9) was proved to be the most effective paint for the longest period at the saltwater test sites. This antifouling paint uses zinc pyrithione as active ingredient and remained in the top 3 paints from Feb 2023 to Oct 2023. EP ZO (PIN 7) is another non-copper antifouling paint that contained zinc pyrithione and performed well in saltwater for several earlier months until algae started to grow on it.

We used SeaVoyage (PIN 19) as control paint because this is a navy-approved coating product in the qualified products list (QPL) on the Naval Sea Systems Command domain. This product is not readily available in the market for commercial use. This paint uses a combination of 7.28% Tralopyril and 6.38% zinc pyrithione as biocides. Panels painted with SeaVoyage® never showed any signs of barnacles or bryozoans' growth. They are also free of discoloration, severe sea mud or incipient algae accumulation for the entire testing period. It is an overall good performing paint in terms of the resistance to a broad spectrum of fouling organisms.

Propspeed® (PIN 11) and Intersleek 1100 SR® (PIN 10) are the only two foul release coatings that don't contain copper or any other biocides in this study. Both paints showed good fouling resistance consistently and especially outperformed others in saltwater in the last 6 months of testing. However, we also observed growth of bryozoans on panels painted with Intersleek 1100 SR®.

On the other hand, several copper-based paints showed promising results for fouling resistance, including CUKOTE, AF33, Sharkskin TM, and PCA Gold. Among copper-based paints, CUKOTE was a top performer as evident in Table 14. All tested copper-based paints are red color except the Interspeed 640 which was black color. Though Interspeed 640 was a copper-based paint found in the Navy's QPL, it underperformed for several months comparing to other paints. From the observation, we hypothesized that differences in color may slightly impact development of a biofouling community on the panel surface and therefore lead to variations in performance. Black paint may absorb more heat from sunlight and favor the environment for marine algal growth in cold weather. However, black antifouling paints could potentially perform better in warm regions where heat limit algal growth. The effect of color on short-term testing of antifouling surfaces was reported in early literatures (Swain et al., 2007; Jin et al., 2019).

Among all tested products, SN-1 is the only product that uses DCOIT as a single biocide. Through review based on safer criteria, we concluded that DCOIT passes the minimum criteria to be safer. However, this product cannot provide comparable performance among the 19 tested products. In the monthly mean fouling resistance ratings, SN-1 either received the lowest or second lowest rating in six out of twelve months.

Yearly mean fouling resistance ratings are also calculated for each location, including the three saltwater sites in Tables 15–17 and the one freshwater site in Table 18. These are determined by averaging the fouling resistance ratings of each paint from each month and for every test location.

Table 15: Yearly mean fouling resistance ratings for Port Orchard.

PIN	% F.R. ratings
19	66.7
1	52.6
2	51.8
3	50.3
4	49.9
5	52.9
6	70.8
7	70.7
8	59.7
9	78.3*
10	87.0*
11	88.1*
12	83.1*
13	69.5
14	63.9
15	72.2
16	65.7
17	68.0
18	53.4

Table 16: Yearly mean fouling resistance ratings for Gig Harbor.

PIN	% F.R. ratings
19	73.6*
1	69.7
2	71.2*
3	63.8
4	63.5
5	54.3
6	53.8
7	69.8
8	38.1
9	85.8*
10	61.8
11	53.4
12	71.2*
13	75.8*
14	70.0
15	64.9
16	63.8
17	61.5
18	57.9

Table 17: Yearly mean fouling resistance ratings for Anacortes.

PIN	% F.R. ratings
19	59.7*
1	54.5
2	50.2
3	43.2
4	44
5	49.2
6	52.8
7	59.7*
8	58.9
9	66.2*
10	64.5*
11	79*
12	58.6
13	54.9
14	58.2
15	52.1
16	51
17	47.3
18	32.8

Table 18: Yearly mean fouling resistance ratings for Seattle.

PIN	% F.R. ratings
19	84.2*
1	69.2
2	64.7
3	70.7
4	68.8
5	83.9*
6	72.7
7	68.6
8	88.9*
9	85.2*
10	83.5
11	82.3
12	78.1
13	73.6
14	73.4
15	73.7
16	73.3
17	80.0
18	59.0

*These values indicate the top 25% performers of all the 19 paints for the entire year-long testing.

As shown in Table 15-17, the yearly mean fouling resistance ratings in saltwater presented consistent results with the monthly mean fouling resistance ratings by months. EP 2000 (PIN 9) remained in the top 25% of all the paints at all four locations. It outperformed the control paint at all locations according to its yearly mean fouling resistance ratings. The yearly mean fouling resistance ratings again highlighted EP ZO, which showed promising results for its performance at all locations and was among top 25% of all paints at Anacortes.

Among other non-copper antifouling paints, the two non-biocidal paints, Intersleek® 1100 SR and PropSpeed® both performed consistently well against fouling. It's worth noting that these two paints were the only two foul release coatings available in the Washington market. They were not used for recreational vessels but were included in this research study to obtain performance data about this type of antifouling paints.

Copper-based paints showed good performances. Among them, CUKOTE (PIN 12) and AF 33 (PIN 13) performed better based on their yearly ratings at all locations.

Paint performance at freshwater site

We recognize that recreational boats often move between saltwater and freshwater or be moored at freshwater site. So, we included a freshwater site in this research study. Due to difference in salinity, the performance can be significantly different. In this study, all paints received higher ratings in freshwater than saltwater in terms of fouling resistance and physical condition. Not much visible destruction of the topcoat and primer can be seen on any of the panels at the Seattle test site, after a year-long of submergence. The yearly mean fouling resistance rating for all paints at the Seattle test site are listed in Table 18.

In Tables 18, the comparison showed that several paints performed better against fouling than others in freshwater. These top performers include SeaVoyage®, Micron CF, and Shelter Island PlusTM and EP SN-1. Notably, EP SN-1 presented outstanding performance for foul resistance in freshwater, even though this paint didn't perform as well as other copper-based and copper-free paints in saltwater. In freshwater where barnacles are not a concern, DCOIT can provide effective fouling resistance to bacterial slime, diatoms, and algae.

Fouling growth in different weather conditions

From the water test readings (Table 5), we observed that the fouling growth on the panels and around the racks increased significantly during the warmer months – March to September 2023. During these months, the water temperature and dissolved oxygen readings were also higher compared to what we recorded in colder months – November 2023 to January 2024. The fouling activity dropped, and the amount of incipient algae was reduced on many panels in colder months, between November 2023 and January 2024.

The correlations analysis has revealed a relatively strong positive correlation between the anti-fouling rating and the dissolved oxygen concentration (DO). That is, as the DO increases, the antifouling performance of the paints tends to increase. On the other hand, there is a relatively strong negative correlation between the antifouling rating and the water temperature. That is, as the water temperature increases, the antifouling performance of the paints tends to decrease. The relationship between the antifouling rating and the water pH exhibits a weak positive relationship because the correlation coefficient is relatively small (0.0635).

It is worth noting that there is a strong positive correlation between water temperature/pH and the DO. In other words, the DO tends to be higher in a warm and more alkaline water body.

Conclusions

For saltwater, freshwater and both, results from Tables 14 and 15 indicate that after the entire year-long performance testing, the top five antifouling paints in order are:

Top 5 antifouling paints for saltwater:

(1) EP 2000: PIN 9, non-copper, biocidal, and non-ablative
(2) Propspeed®: PIN 11, non-biocidal, and non-ablative
(3) CUKOTE: PIN 12, biocidal copper-based, and ablative

(4) Intersleek® 1100 SR: PIN 10, non-biocidal, non-biocidal and non-ablative
(5) EP ZO: PIN 7, non-copper, biocidal, and ablative

Top 5 antifouling paints for freshwater:

(1) EP SN-1: PIN 8, non-copper, biocidal, and ablative
(2) EP 2000: PIN 9, non-copper, biocidal, and non-ablative
(3) Smart Solution: PIN 5, non-copper, biocidal, and ablative)
(4) Intersleek® 1100 SR: PIN 10, non-copper, non-biocidal and non-ablative
(5) PropSpeed®: PIN 11, non-copper, non-biocidal and non-ablative

Top 5 antifouling paints for both saltwater and freshwater (overall best):

(1) EP 2000: PIN 9, non-copper, biocidal, and non-ablative
(2) Propspeed®: PIN 11, non-biocidal, and non-ablative
(3) Intersleek® 1100 SR: PIN 10, non-copper, non-biocidal and non-ablative
(4) CUKOTE: PIN 12, biocidal copper-based, and ablative
(5) AF 33: PIN 13, biocidal copper-based, and ablative

The ASTM standard method states to use the control paint (in this case SeaVoyage®, PIN 19) as the standard paint, and rate test paints or panels based on the control paint. For instance, if the control (PIN 19) received a mean overall performance rating of 77 in saltwater, the highest-rated test paint cannot have a mean overall performance greater than 77, even if it is completely void of fouling and any physical defects. This approach, however, is not adopted for this study. The control paint is treated as an antifouling paint for comparison purposes. Therefore, each paint is rated individually on its antifouling performance and is not affected by the rating of the control.

Note that SeaVoyage® is a U.S. Navy-approved paint and is not easily available to the public. It was selected from the U.S. Navy qualified product list of antifouling paints and was replaced with the lead-based paint mentioned in the ASTM standard after discussing it with the ASTM committee.

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Appendix B: Acronyms and Abbreviations

Table 19: Acronyms, abbreviations, and definitions

Term	Definition
A.C.	Anticorrosive film
A.F.	Antifouling film
ASTM	American Society for Testing and Material
BM-1	Benchmark 1
BM-1^{TP}	The subscript means the transformation products drive BM score
BM-2	Benchmark 2
BM-3	Benchmark 3
BM-4	Benchmark 4
BM-U	Benchmark Unknown
Cu_2O	Cuprous Oxide
DCOIT	Dichlorooctylisothiazolinone
Ecology	Washington Department of Ecology
ECONEA	Tralopyril
EPA	Environmental Protection Agency
EU	European Union
F.R.	Fouling resistance
O.P.	Overall performance
PFAS	Per and polyfluoroalkyl substances
PIN	Panel identification number
RCW	Revised Code of Washington
UV	Ultraviolet light
WSU	Washington State University

Appendix C. Flowchart Plain Text

Flowchart of overview of the Process to Determine Whether a Chemical Alternative is Safer:

Does the priority chemical class meet the minimum criteria for safer?

If yes, then answer the following:

- Does the alternative meet the additional criteria for safer?
  - If Yes, it is a safer alternative.
  - If No, evaluate special considerations.

If no, then answer the following:

- Does the alternative meet the minimum criteria for safer?
  - If No, evaluate special considerations.
  - If Yes, it is a safer alternative.