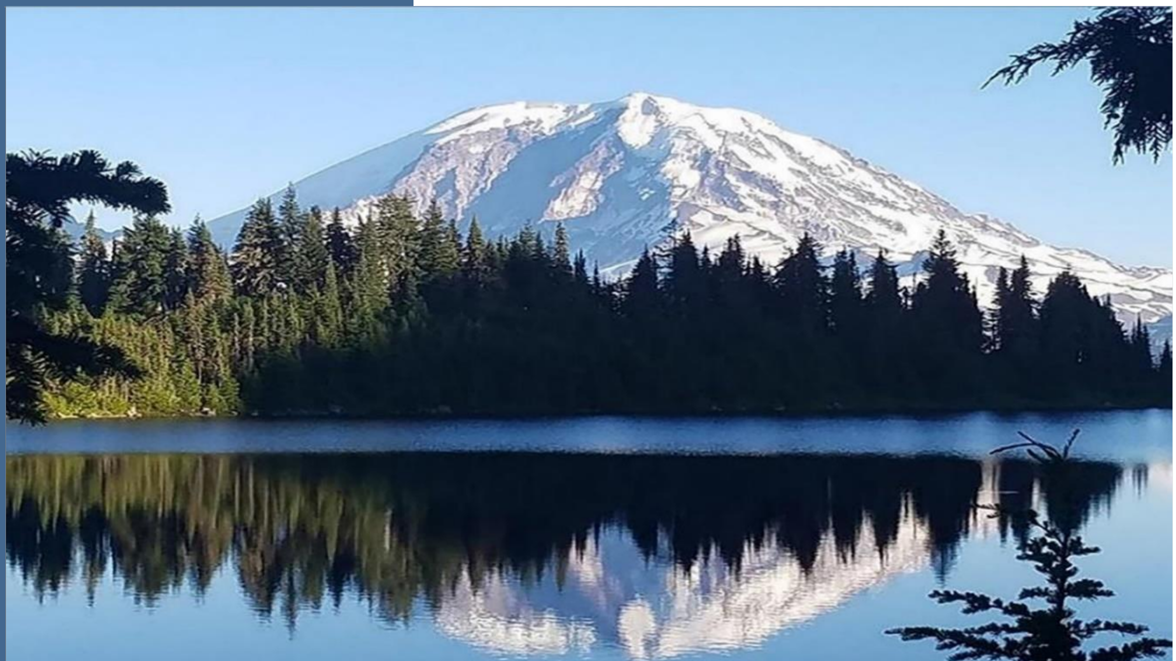

Draft Antifouling Paints in Washington State: Third Report to the Legislature

Hazardous Waste & Toxics Reduction Program

Washington State Department of Ecology

Olympia, Washington

November 2023, Publication 23-04-057

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Antifouling Paints in Washington State: Third Report to the Legislature

Pursuant to RCW 70A.445.020

Hazardous Waste & Toxics Reduction Program

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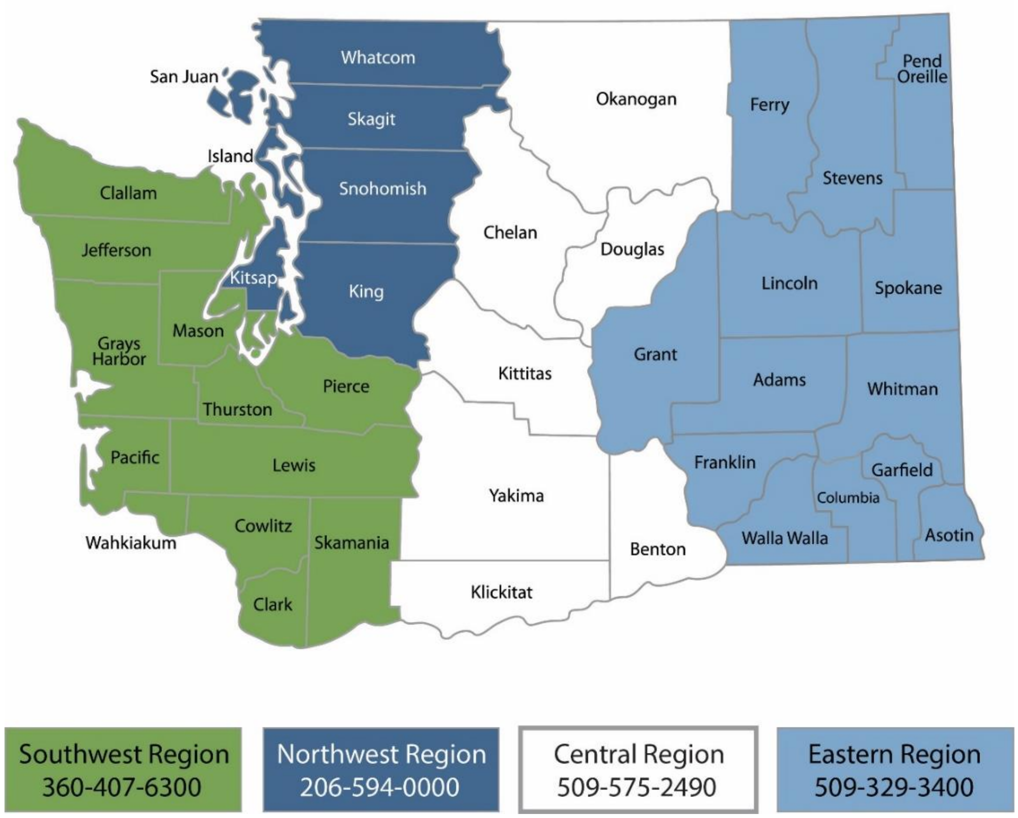
Department of Ecology's Regional Offices

Map of Counties Served



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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, recreational boaters use antifouling paints on boat hulls to either prevent fouling organisms from attaching or make it easier for them to dislodge. However, antifouling paints usually rely on biocides and other toxic chemicals to work.

Copper-based 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 State has concerns about the release of copper and other toxic chemicals into the aquatic environment.

In 2011, the Washington State Legislature passed legislation to phase out the use of copper-based antifouling paints. Ecology conducted two surveys in 2017 and 2019 to investigate the availability and environmental impact of alternative antifouling products. 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 the ban on copper-based paints in both 2018 and 2020. In 2020, Ecology was directed to continue searching for safer and effective alternatives to copper.

This report summarizes the results of Ecology's review as directed by the Legislature. It consists of a scientific review of biocidal and non-biocidal paints and ingredients. It focuses on new scientific information that recently became available. In this report, we define what could be considered as safer, effective, feasible, reasonable, and readily available, respectively. In particular, we developed hazard-based criteria to determine whether chemicals are safer or not.

During our review of biocidal ingredients, we found non-copper antifouling biocides registered for use in the Washington State have remained essentially unchanged since our last review in 2019. Based on the new scientific information reviewed, Ecology concluded that Tralopyril/Econea and zinc pyrithione are not safer replacements to copper. DCOIT is a safer chemical to copper based on our current knowledge, but we lack sufficient data to conclude the 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. Very limited 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 still 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 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 State has a long legislative history concerning copper antifouling paint. In 2011, due to concerns about copper's potentially adverse impact on salmon, the Antifouling Paints Law[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, water quality, and 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 more 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.

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

Background

When structures are immersed in the marine environment, they are subjected 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 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 used biocide in paint. Non-biocidal paints work by creating an ultra-smooth or durable hard surface that is easy to clean.

Copper

Copper has been the dominant active ingredient in antifouling paints since the phase out of tributyltin (TBT). Copper effectively kills many different types of fouling organisms. Copper-based hull paints generally rely on the leaching of copper to create an effective dose. However, as a result of long-term use in overloaded area, 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 to copper 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 pesticides by the Washington State Department of Agriculture (WSDA) and the United States Environmental Protection Agency (EPA) under authority from the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). Starting in 2019, EPA adopted a “maximum allowable leach rate” for antifouling paints that contain copper. These paints may not release more than 9.5 µg of copper per cm^2 of painted surface per day, or else they do not qualify for registration under FIFRA (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 ug/L to 44 ug/L 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 usually contain one or more chemically active 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).

In the U.S. and Washington State, all biocidal paints are registered with the U.S. EPA and WSDA. The pesticide registration information in Washington is available to the public through the Washington State University's Pesticide Information Center Online Database (PICOL).[5]

A review of the PICOL database confirms that copper-based biocides are in 73 out of 87 registered products.[6] The forms of copper are dominantly cuprous oxide, followed by cupric oxide, copper pyrithione, and cuprous thiocyanate. Copper-free biocidal ingredients registered for use in Washington State are limited to Tralopyril, zinc pyrithione, and DCOIT (Dichlorooctylisothiazolinone).

In addition to biocides, antifouling paints usually use other compounds in the formulations. The quantitative composition is summarized as follows (Watermann et al., 2019).

- Matrix or polymeric binder (20–30%)
- Core Biocides (15–40%)
- Co- or Booster Biocides (4–5%)
- Erosion Additives like zinc oxide (5–15%)
- Pigments (3–4%)
- Plasticizers (2–5%)
- Catalysts (0.5–2%)
- Solvents (15–20%)

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 antifouling paints. Non-biocidal paints contain silicone, ceramic, or epoxy material. These paints are categorized into three types based on their working mechanisms:

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[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 PICOL in August 2023.

- **Foul release coatings (FRCs):** Foul release coatings are the leading market alternatives to traditional biocidal coatings. They create a smooth surface that does not dissolve in water. FRCs work by preventing the attachment of fouling organism through physical rather than chemical action. These coatings have either silicone elastomer (PDMS), 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 (SPCs)**: 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 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 can 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 FRCs and SPCs are commercially available, they are primarily developed for commercial vessels and propellers rather than recreational boats.

Our 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 conditions.
- 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. Ecology did not intend to 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 guide and other programs like Safer Products for Washington to help define parameters. The Safer Products for Washington program identifies the products that are significant sources of high-priority chemicals and make regulatory determinations to reduce them. It is a separate program from the antifouling project but has established methods in identifying safer alternatives.

Safer antifouling chemicals are less hazardous to non-target species, less persistent and less bioaccumulative, 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 in 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 it in this report as a guidance for future searches for safer antifouling ingredients.

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.

Effectivity and reasonableness have not been used as metrics in other alternatives assessments that we have produced but can be thought of as slightly 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 State, we collaborated with a research team at Washington State University and conducted a performance field test of already available paint alternatives. The performance test uses industry standard method and rate each product with a score based on fouling coverage and types of fouling (ASTM, 2020). The research team compares 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 boat.

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[7] 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.[8] 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 less bioaccumulative.
- Release fewer toxic chemicals into the environment.

Scope

This safer criteria specifically focuses 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 like 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. Use of this approach towards inactive chemicals, chemicals with other functions, or chemicals used in structures other than boat hulls is not within the scope of this review.

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

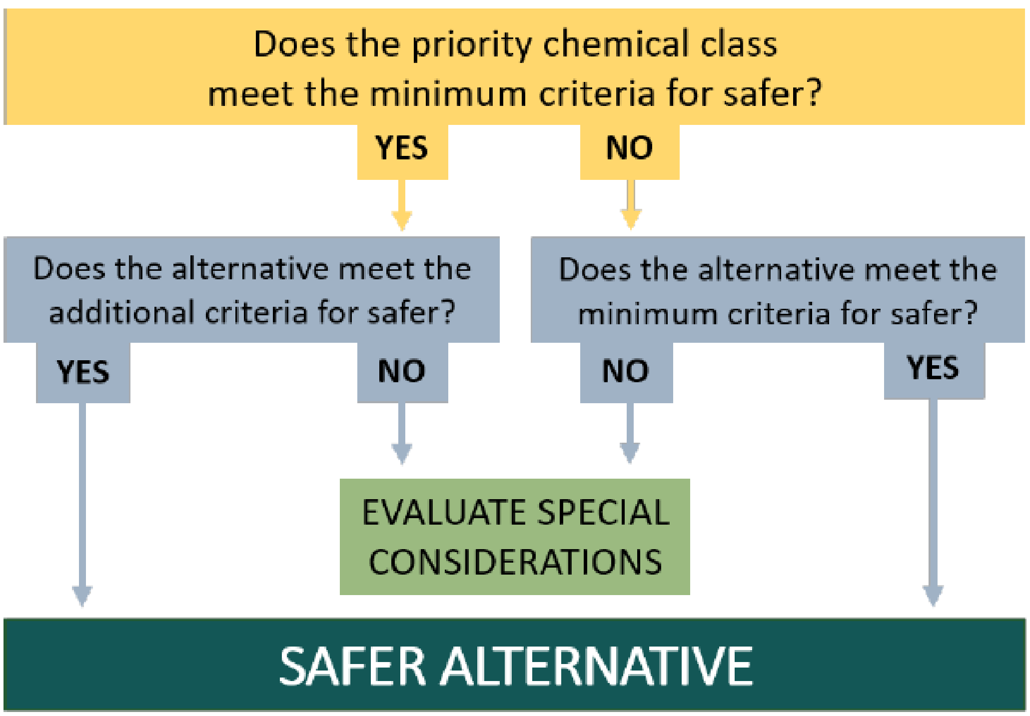
[8] https://apps.leg.wa.gov/rcw/default.aspx?cite=70A.445

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 safer 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[9] with modifications and special consideration (Ecology, 2021a). Safer Products for Washington safer criteria include minimum and additional requirements to identify safer alternatives. Figure 1 demonstrates the general process to determine chemicals as safer.

Figure 1: Overview of the general process used to determine whether alternatives are safer (Ecology, 2021).



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 (SCIL) master criteria.

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

GreenScreen® for Safer Chemicals is a method of comparative Chemical Hazard Assessment (CHA). Entities such as OECD, 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 GreenScreen® for Safer Chemicals methodology, chemicals receive a combined "benchmark score" based on the assessments of 18 hazard endpoints. 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 will use the same process and criteria to compare alternative chemicals to copper-based antifouling chemicals. Though those copper-based chemicals are inorganic, all alternatives to be considered are organic chemicals and the Safer Products for Washington safer criteria are applicable 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.

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.

Hazard endpoint	Requirement
Carcinogenicity	Required
Mutagenicity/Genotoxicity	Required
Reproductive or Developmental Toxicity	Required
Endocrine Disruption	Not required
Acute Toxicity	Not always required*
Single or Repeat Systemic Toxicity	Not always required*
Single or Repeat Neurotoxicity	Not always required*
Skin or Respiratory Sensitization	Required
Skin or Eye Irritation	Not required
Acute or Chronic Aquatic Toxicity	Required
Persistence	Required
Bioaccumulation	Required

***Two of three required**

Among the required data, acute or chronic aquatic toxicity is particularly important, but 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. This modification means that we classify hazard levels based on environmental fate and transport endpoints using only 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 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 choose to define the most representative biofouling species and assume that the remaining available data will be mostly from non-target species.

Organisms that are considered non-target organisms include fish, sea urchin, 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 State, 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 (Baldwin et al, 2003; McIntyre et al., 2008, 2012; Sandahl et al., 2007; Hecht et al., 2007). Salmon are sensitive non-target species. Based on our criteria, available toxicity data from salmon are 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 for safer, 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 will consider 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 State. 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.

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.

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, Europe (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.

As a summary of new information, copper is still 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 State: 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 U.S. in 2007 and in the EU in 2014. It is listed as an ingredient in 11 out of 87 products registered for use in Washington State, typically at a concentration of 6%.[10] 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 ug/L, 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.

As a summary of the new information, Tralopyril turns into persistent chemicals after hydrolysis. It exhibits high ecotoxicity and pose concerns on human health risks.

Zinc pyrithione

Zinc pyrithione is one of the most frequently used alternative biocides to copper. A review of the PICOL 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.

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[10] Registration information may change over time. This data only reflects the information obtained from PICOL in August 2023.

Zinc pyrithione is persistent in the environment, especially in lower water column or in the sediment where UV light is not available. It breaks down in the saltwater environment through photolysis, 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 to 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 assessment, zinc pyrithione has high developmental toxicity, very high acute toxicity, and systemic toxicity. Based on an authoritative rating from EU harmonized classification H360, zinc pyrithione was rated as a chemical with high developmental toxicity in humans and "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 with 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 approved to use in the U.S. in 2015. There are currently seven products registered for use in Washington State 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 break 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. With a low log K_{ow} value of 2.8, this chemical 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 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, a banned antifouling biocide in the US (Onduka et al., 2022; Hyun et al., 2022).

Earlier monitoring studies have reported DCOIT in the seawater at ppb 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 State.

As a summary of new information, DCOIT exhibit 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 minimal criteria and be considered as “safer.” The decision-making process incorporates additional data review in the minimal 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-1_{TP}, where the subscript “TP” means that one or more transformation products drives the Benchmark score. GreenScreen® Benchmark scores, except BM-1, expire after five years.

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 changed to BM-1. In Table 3, we summarized 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	Mutagenicity	Reproductive Toxicity	Developmental Toxicity	Endocrine Activity	Acute Toxicity	Systemic Toxicity	Systemic Toxicity, Repeated dose*	Neurotoxicity	Neurotoxicity, Repeated dose*	Skin Sensitization*	Respiratory Sensitization*	Skin Irritation	Eye Irritation	Acute Aquatic Toxicity	Chronic Aquatic Toxicity	Persistence	Bioaccumulation	Reactivity	Flammability
1317-39-1	Cu_2O	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 minimal requirements for safer. DCOIT, as a BM-2 chemical, passes the minimal criteria due to low persistence and very low bioaccumulation. We conclude that DCOIT is a safer antifouling chemical comparing to copper, based on currently available information. Though DCOIT is safer than copper, it still presents significantly high acute and chronic toxicity to non-target species.

Review on effectiveness

Based on our definition on 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 Washington State conducted an Alternatives Assessment in 2017 (TechLaw and NGC, 2017). This report evaluated paint performance based on San Diego report results and Practical Sailor panel testing, supplemented by customer reviews from purchasing websites and boating forums (SDUPD and IRTA, 2011). We checked new information from similar resources and found limited updates. We 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 literature reported results from efficacy testing of antifouling products for sea-based salmon farming based on the ASTM method. None of the products using Econea 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 of the Atlantic Ocean, a test from a real immersion scenario showed that products with Econea 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 (RIVM) 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 contain 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 the 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 HP 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 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 source, we cannot conclude the effectiveness of DCOIT.

In order to fill this data gap, we collaborated with a research team at Washington State University and conducted a performance field test. The initial performance testing results are included in this report, but testing is ongoing.

Other biocides

All biocides are subject to strict regulation through pesticides registration in the U.S. and Washington State. In addition to risk assessments done during in the initial registration, EPA reviews each registered pesticides at least every 15 years.

There are some other biocides registered for use in Europe and other counties. For example, Dichlofluanid, Medetomidine, Zineb, and Tolyfluanid are four additional biocides registered in EU BPR P21. 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 soon to replace copper.

Non-biocidal alternative paints

Due to regulatory pressure and environmental concerns, more active research is shifting to focus on non-biocidal alternative paints. Typical non-biocidal paints include foul release coatings (FRCs), biocide-free self-polishing coatings (SPCs), 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 boats. 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 alternative 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 (FRCs) are the leading market alternatives to traditional biocidal coatings. However, the main drawback is idle periods and poor mechanical strength. FRCs depend on physical action, such as a vessel moving through the water, to “release” the weakly adhered organisms. FRCs 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 FRC product and most of them are only available to commercial shipping market (Kim et al., 2021). Examples include:

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

Though foul-release coatings have started to be available in the market, their environmental impact is unknown. Companies do not 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 FRCs, a 2021 California study found three out of four non-biocidal coatings contain high levels of 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 concerning pollutants in the marine environment. Washington State restricts intentionally added PFAS in several consumer products due to concerns in persistence, bioaccumulation, and adverse human health impact (Ecology, 2021b; Ecology, 2022). Ecology cannot support the use of PFAS as a substitute for copper in antifouling paints.

For silicone-based FRCs, literature has mentioned that hydrophilic-modified silicone oils are leaching 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, the substances leaching from foul release coating are unknown. Substances that are being released to the environment may include catalysts, unreacted components that migrate to the surface of the polymer, solvents, or low levels of toxic compounds in pigments and other additives. The antifouling paint particles that contain these substances can contribute to marine contamination as microplastics. We lack sufficient information to conclude 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 led to significantly less fouling compared to self-polishing copper-containing paint (Oliveira et al., 2020). Similarly, another study in 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 about the efficacy of foul-release coatings in Washington. To address the data gap, we are conducting a performance testing in Washington, including two non-biocidal paints.

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 SPCs. The composition and effectiveness of this paint are 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 hydrojetting (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 State. Commercial vessels' washing efforts must follow Washington State's guidance on hull cleaning in Washington State waters.[11] 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 surface (Yan et al., 2020; Hao et al., 2022; Liu et al., 2020). However, major challenges remain in the commercialization of the natural products. For example, the process to extract active ingredients from raw materials on a large scale can be technically difficult before they can be added to the coating formulations. Natural products are not necessarily safer than synthetic chemicals. The effectiveness, safety and toxicity of natural products still needs verification through substantial 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.

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

Cleaning in haul-out facilities is a highly effective antifouling technique with less environmental impact. In Washington State, 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 environment impact.

Feasibility of best management practices

The use of best management practices (BMPs) 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 BMPs, 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 BMPs for point source discharges control during the painting, cleaning and maintenance upland or in-water.

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

- It prohibits pressure washing wastewater from discharge directly to waters of the state and requires that pressure wash areas decontaminate after use.
- It requires vessel hulls only be sanded using vacuum sanders to collect dust, placing restrictions on in-water maintenance and hull work, restricting upland vessel maintenance activities, and requiring 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 BYGP (2022) reduces the limit for copper content in wastewater discharged to a non-delegated publicly owned treatment works (POTW), and the benchmark for stormwater discharged to surface waters. When source control BMPs 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 (BMPs) and provide copies to all employees, contractors, boat owners, and other customers, as appropriate." The permit requires the list of BMPs in a facility specific document called the Stormwater Pollution Prevention Plan (SWPPP).

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

There are effective BMPs for controlling non-point sources of copper pollution. In-water hull cleaning of boats is banned in Washington state. Commercial vessel ship hull cleaning is allowed under the Vessel General Permit ("VGP," soon to be replaced with "Vessel Incidental Discharge Act, "VIDA"). State specific guidance can be found on the [Focus for In-Water Hull Cleaning publication](https://apps.ecology.wa.gov/publications/SummaryPages/1410012.html),[12] issued in 2014.

[12] 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 antifouling 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 Material method (ASTM, 2020). This test mimics actual use of these paints. So rather than using aquatic species toxicity as a proxy for effectiveness, we can instead directly measure the relative percentage of fouling coverage on painted panels in water. A static exposure test with coated panels is a worst-case scenario and will give most demanding conditions for efficacy of antifouling paints.

We monitor and evaluate the overall fouling condition each month in this field study. We plan to use the performance test to fill in data gaps in assessing the feasibility of alternatives.

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 include 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. They either have heavy boat traffic or serve as a long-term boating 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, 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. The application followed ASTM standard test method, and OEM's technical data sheets (TDS). 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. A "tie and tack coat" was required for certain paints and was applied following instructions from TDS. 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 will last for 12 months. Once per month, the researchers observe each panel individually, record the data, and report the biofouling based on the test method. In addition to fouling monitoring, the researchers also record water physicochemical parameters such as temperature, salinity (conductivity), and pH.

At the end of the test, panels will be gently washed with tap water to remove any loosely adhered sea mud, slime, or weed. This will eliminate incipient fouling (especially algae) occurring on the panels. Any incipient fouling is reported and photographed. The method defines a scoring system for qualitative data. After a 12-month examination, a final score will be made based on:

- Physical condition.
- Non-colonial forms such as barnacles and coelenterates in numbers and sizes.
- Colonial forms such as algae by percent surface covered.

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

Six-month preliminary results

We include a full presentation of six-month preliminary results from performance testing in Appendix A. At this point, we cannot draw solid conclusions based on an incomplete dataset. Instead, we observed a few trends from the results, and these are subject to changes.

The seven copper-based paints contain cuprous oxide ranging from 25% to 47.5%. After six months, some test panels have thin layers of biofilm, and most didn't have any barnacles attached. There were no obvious differences observed among the different copper-based paints. The top performing paint at six months, Seahawk AF-33, has relatively lower copper content comparing to others.

The ten non-copper paints contain either Tralopyril, zinc pyrithione, DCOIT, or a combination of two of these ingredients. Non-copper paints presented satisfactory performance among separate locations. The top performing paints include Pettit Hydrocoat Eco, Interlux Pacific Plus, EPAINT EP-2000, and Pettit Eco HRT. We found the use of zinc pyrithione, or a combination of Tralopyril and zinc pyrithione, effectively prevented the test panels from fouling within the testing period. The product that uses DCOIT received the lowest performance score at 6 months.

We can only find 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 remains intact after six months in most locations.

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 will not sufficiently prevent biofouling. The Biocidal Products Regulation (BPR) in the EU 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 six-month data, we found popular copper-based, non-copper based, and non-biocidal paints all have satisfactory performance. However, the safer biocide, DCOIT, present relatively low performance. The performance test will continue and conclude in January 2024. We look to update this report and Appendix A with final results and conclusions.

Final results

We plan to update this report and the appendix A with final results and conclusions when they’re available.

Conclusions

In 2020, the Washington State 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 definition to safer, effective, feasible, reasonable, and readily available.

Ecology developed criteria for 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 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 U.S. and Washington State. 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 show it is 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 minimal 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 evaluate alternatives, Ecology started a performance test on antifouling products. The preliminary results at 6 months show that product based on DCOIT presented the lowest performance among non-copper biocidal paints, and work less effectively than average copper paints in Puget Sound 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 State.

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 using PFAS. We found that studies discussing the environmental risks and toxicities of these paints and ingredients are not sufficient to conclude their safety.

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 pesticides registration and review process. We don’t see new biocides likely to become readily available soon.
- Non-biocides are under development. We lack sufficient data about the composition and possible leachables 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 Preliminary Results

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Introduction

This report is based on the results gathered (six months) from the ongoing performance testing to evaluate effectiveness alternatives to copper antifouling paints. The testing is meant to last one calendar year and is expected to finish by January 2024. Four locations in Puget Sound Washington including Port Orchard, Gig Harbor, Seattle (west), and Anacortes are used to submerge steel panels in the real ocean and lake water sites. Seattle (west) is the only lake water testing location. A total of 19 panels are submerged in each location including one control. Data is being collected monthly and in this report data from the end of six months of testing is presented. It may help in understanding how copper and non-copper-based antifouling paints are performing in real ocean and lake water.

A Quality Assurance Project Plan (QAPP) was published for this research project in which details of project description, quality objectives, study design, field procedures, and data verification were provided. This report is prepared in the light of already published QAPP and the available ASTM standard test method for testing antifouling panels in shallow submergence. It includes actual photographic evidence of panels' conditions from all locations at the end of 6 months of testing.

Materials and Methods

Antifouling paints

The antifouling paints used in this research were either copper or non-copper based. All of them are biocidal, except two. Several of these are ablative (self-polishing) paints. Table 4 has the details for all the paints, including the control paint. The panel identification number (PIN) the name of the paints used on each, are provided in Table 4.

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

PIN	Paints	Nature	Biocidal	Ablative
1	Hydrocoat® ECO	Non-copper	✓	✓
2	ECO HRT®	Non-copper	✓	X
3	Micron CF	Non-copper	✓	✓
4	Pacifia Plus	Non-copper	✓	✓
5	Smart Solution	Non-copper	✓	✓

PIN	Paints	Nature	Biocidal	Ablative
6	Shelter Island Plus™	Non-copper	✓	✓
7	EP-ZO	Non-copper	✓	✓
8	SN-1	Non-copper	✓	✓
9	EP-2000	Non-copper	✓	X
10	Intersleek® 1100 SR	Non-copper	X	X
11	Propspeed®	Non-copper	X	X
12	CUKOTE	Copper-based	✓	✓
13	AF 33	Copper-based	✓	✓
14	Sharkskin™	Copper-based	✓	X
15	PCA Gold	Copper-based	✓	✓
16	Micron® CSC*	Copper-based	✓	✓
17	Fiberglass Bottomkote® NT	Copper-based	✓	✓
18	Interspeed 640	Copper-based	✓	✓
19	SeaVoyage®	Non-copper	✓	✓

Panels, racks & ropes

Panels are A569 steel plates 11 gauge (0.12” thick and 9x9 in^2) and were sandblasted according to TDS, prior to applying any paints. The exposed and painted area for each panel is 81 in^2.

Racks are marine-grade high-density polyethylene (HDPE), and they are either 4 * 1 ft^2 or 2.2 * 1 ft^2. Longer racks accommodate eight panels – four on each side. Smaller racks have three panels, two on one side and one (control) on the other.

After the paints were applied on each panel by following manufacturer-provided technical data sheets (TDS) and fully cured (no tacky state), they were mounted on racks using fiberglass-made studs and hex nuts to avoid corrosion. The racks were then submerged in water only after the minimum time prior to flooding and before the maximum time prior to flooding. Prior to flooding the final thickness of the paint system was measured for each panel. Racks were submerged between 1.5 to 3 feet deep below water. Figure 2 shows the racks with panels mounted, before submerging into water.

Figure 2: Test panels mounted on the rack prior to submerging into water at Seattle, WA.

Ropes used initially to tie the racks with the piers or docks, or rafts were polypropylene (yellow), but they were replaced after a few months of monitoring. They were quickly degrading under sunlight and were replaced by ¼” Nylon 3-strand rope.

At the Seattle Yacht Club (SYC), cleats were mounted to support the racks.

Standard test method – ASTM D3623 – 78a

Most of the guidelines for completing this testing were taken from the ASTM standard test method for testing antifouling panels in shallow submergence (ASTM, 2020). However, there were minor deviations as well as some additional details. For instance, instead of just one location, we are testing on four separate locations. Since, there were a lot of panels to be prepared and due to the limitation of maximum time before flooding, it was not possible to use duplicates or triplicates for each paint on each location. Rather than duplicating panels for each paint product, we chose more ocean water locations. For the results from the only lake water test site, to suffice the repeatability we will consider dividing each panel’s photograph into four equal areas and will consider each smaller area as a replicate. This will be done for the final report. For this report, the fouling resistance (F.R.) is reported for each panel (paint) by taking the average of F.R. from all three ocean water sites, using data at the end of 6 months of testing. For the lake water site, the F.R. is reported as such. ASTM provides a method to report antifouling paint performance in terms of percent ratings. Together with F.R., the physical condition which includes the condition of the antifouling film (A.F.) and anticorrosive film (A.C.), contribute to the overall performance (O.P.) (ASTM, 2020).

To report the performance of antifouling paint, each test panel surface will be awarded a rating of 100 if no visible incipient or mature fouling (colonial or non-colonial) is present. Biological slime (Jelly-like slimy gray or clear mold and algal spores (mostly microscopic) do not contribute to ratings. The rating will be reduced to 95 if only incipient fouling is present on the panel. If any mature form of fouling is present, the number of individuals present for non-colonial fouling such as barnacles or encrusting bryozoans, the percent area covered by colonial fouling, like algae, will be subtracted from 95 to obtain a rating for F.R. For A.F., a panel will receive a rating of 100 if no physical defects in antifouling paint, the top layer, are present, otherwise percent area affected by such defects will be subtracted from 100 to obtain the final A.F. rating. Rating criteria similar to A.F. will be followed for A.C. The lowest rating number of all three ratings, F.R., A.C., and A.C., will be selected as the O.P. rating. Results based on these criteria are reported in Table 16 and 17.

QAPP – Study objectives and procedures

In the published QAPP, the objectives for this research project have been elaborated (Ecology, 2023). Most of these objectives are to be met based on the ASTM standard method. For a comparative study, ratings obtained from test panel paints and the control panel paint, Sherwin Williams SeaVoyage®, will be compared with each other.

For measurement and sampling procedures, as indicated in QAPP, the ASTM method is mostly followed. Panels were photographed monthly with a high-magnification digital camera with or without the aid of blackout cloth and sunlight-blocking papers. In addition to ASTM guidelines, researchers tested pH, temperature, dissolved oxygen (DO), and conductivity of water at all locations on each monthly visit. The results are illustrated in Tables 5-10.

Final report

Because incipient fouling, as well as biological slime, are often present on the panels, at the end of a year-long testing the panels will be washed with tap water. The washing will be manually done by gently flowing tap water on panels so as not to disturb any mature fouling. Photographs will be taken prior to and after the washing process, to identify any loosely adhered incipient fouling. Washing will ensure that there are no loosely adhered marine contaminants including sea mud, soil, weed, etc., on the panels, before they are rated for the antifouling performance. This washing has not been done until now for any of the panels on any test site. That is why in several images, loosely adhered seaweed, mud, and soil are prominent. Furthermore, data analysis and presentation methods will be looked over for the final report. These may include analysis of variance (ANOVA), principal component analysis (PCA), and plotting monthly data to illustrate temporal evaluation. Proper sample IDs will be used in the final report, however, for this report only PIN is used for each painted panel.

Results

Water tests – pH, temperature, conductivity and DO

Results of water-based tests, performed monthly on each test site are shown in Tables 5-10.

Table 5: Temperature, pH, conductivity and DO of ocean and lake water on test sites in February 2023.

Test location February 2023	Temp (°C)	DO (mg/L)	pH	EC* (mS/cm)	Hardness (ppm)
Port Orchard	8.8	11	7.45	N/A	425+
Gig Harbor	8.3	11.3	7.8	N/A	425+
Seattle	7.8	13.1	8.1	0.09	45
Anacortes**	7.5	-	-	-	-

Table 6: Temperature, pH, conductivity and DO of ocean and lake water on test sites in March 2023.

Test location March 2023	Temp (°C)	DO (mg/L)	pH	EC* (mS/cm)	Hardness (ppm)
Port Orchard	8.8	10.4	7.9	N/A	425+
Gig Harbor	8.3	11.3	7.8	N/A	425+
Seattle	7.9	12.6	8	0.08	50
Anacortes	7.5	11.6	7.8	N/A	425+

Table 7: Temperature, pH, conductivity and DO of ocean and lake water on test sites in April 2023.

Test location April 2023	Temp (°C)	DO (mg/L)	pH	EC* (mS/cm)	Hardness (ppm)
Port Orchard	10.3	10.1	7.9	N/A	425+
Gig Harbor	12.1	11.3	8.1		
Seattle	11.2	10.4	8	0.08	50
Anacortes	10	10.4	7.9	N/A	425+

Table 88: Temperature, pH, conductivity and DO of ocean and lake water on test sites in May 2023.

Test location May 2023	Temp (°C)	DO (mg/L)	pH	EC* (mS/cm)	Hardness (ppm)
Port Orchard	12.2	10.4	8	N/A	425+
Gig Harbor	15.2	12.5	8.1	N/A	425+
Seattle	21	10.8	8.8	0.08	50
Anacortes	14.2	13.2	8.3	N/A	425+

Table 99: Temperature, pH, conductivity and DO of ocean and lake water on test sites in June 2023.

Test location June 2023	**Temp (°C)**	**DO (mg/L)**	**pH**	**EC* (mS/cm)**	**Hardness (ppm)**
Port Orchard	14.8	11.5	7.8	N/A	425+
Gig Harbor	18.3	13	8	N/A	425+
Seattle	21.1	9.9	8.6	0.08	50
Anacortes	14.7	11.4	8.2	N/A	425+

Table 1010: Temperature, pH, conductivity and DO of ocean and lake water on test sites in July 2023.

Test location July 2023	**Temp (°C)**	**DO (mg/L)**	**pH**	**EC* (mS/cm)**	**Hardness (ppm)**
Port Orchard	14.1	10.9	7.9	N/A	425+
Gig Harbor	18.3	13.1	8.1	N/A	425+
Seattle	25.5	17.6	10.2	0.09	60
Anacortes	15.8	10.5	7.7	N/A	425+

Table 1111: Temperature, pH, conductivity and DO of ocean and lake water on test sites in August 2023.

Test location July 2023	**Temp (°C)**	**DO (mg/L)**	**pH**	**EC* (mS/cm)**	**Hardness (ppm)**
Port Orchard	13.9	9.2	7.6	N/A	425+
Gig Harbor	17	12.5	7.8	N/A	425+
Seattle	22.2	9.7	8.8	0.09	50
Anacortes	14.1	9.1	7.7	N/A	425+

∗*Electrical Conductivity*

∗∗*For Anacortes, we had to move panels to a new location after re-painting or touching most of the panels due to excessive water turbulence from ferry engine turbines.*

as *for the months of Feb and March 2023, the water temperatures are recorded from an online source (weatherspark.com, wrcc.dri.edu)*

Due to the turbulence issue at Anacortes Ferry Terminal, which was the initial testing site at Anacortes, we had to bring the panels back to WSU Pullman for touching and re-painting. We then submerged them at the new test site in Anacortes in March 2023. So, for Anacortes, it will be 6 months in September. Therefore, we are sharing only 5 months (from Aug 2023) of data for Anacortes for now. It is possible that we may not be able to complete one full calendar year of testing at Anacortes.

Paint system thickness measurement

Before flooding the panels in water, the final thickness, in microns, of the antifouling paint system for each panel was measured, on each test site. The values are provided in Table 12-15.

Table 12: Mean final thickness (T) of paint system on each panel before flooding (Jan 2023) at Port Orchard site.

Paint	T (µm)
Hydrocoat® ECO	496
ECO HRT®	377
Micron CF	504
Pacifia Plus	495
Smart Solution	635
Shelter Island Plus™	343
EP-ZO	488
SN-1	450
EP-2000	282
Intersleek® 1100 SR	323
Propspeed®	74
CUKOTE	442
AF 33	339
Sharkskin™	387
PCA Gold	162
Micron® CSC*	395
Fiberglass Bottomkote® NT	458
Interspeed 640	276
SeaVoyage®	245

Table 13: Mean final thickness (T) of paint system on each panel before flooding (Jan 2023) at Gig Harbor site.

Paint	T (µm)
Hydrocoat® ECO	407
ECO HRT®	320
Micron CF	454
Pacifia Plus	453
Smart Solution	497
Shelter Island Plus™	377
EP-ZO	469
SN-1	404
EP-2000	277
Intersleek® 1100 SR	305
Propspeed®	28
CUKOTE	385
AF 33	374
Sharkskin™	408
PCA Gold	166
Micron® CSC*	393
Fiberglass Bottomkote® NT	469
Interspeed 640	268
SeaVoyage®	255

Table 14: Mean final thickness (T) of the paint system on each panel before flooding (Jan 2023) at Seattle (west) site.

Paint	T (µm)
Hydrocoat® ECO	405
ECO HRT®	318
Micron CF	513
Pacifia Plus	460
Smart Solution	418
Shelter Island Plus™	298
EP-ZO	532
SN-1	418
EP-2000	260
Intersleek® 1100 SR	276
Propspeed®	59
CUKOTE	235
AF 33	387
Sharkskin™	378
PCA Gold	146
Micron® CSC*	372
Fiberglass Bottomkote® NT	415
@EInterspeed 640	249
Sea Voyage®	319

Table 15: Mean final thickness (T) of the paint system on each panel before flooding (Jan 2023) at Anacortes site.

Paint	T (µm)
Hydrocoat® ECO	447
ECO HRT®	351
Micron CF	490
Pacifia Plus	440
Smart Solution	445
Shelter Island PlusTM	333
EP-ZO	506
SN-1	530
EP-2000	346
Intersleek® 1100 SR	329
Propspeed®	75
CUKOTE	396
AF 33	416
SharkskinTM	418
PCA Gold	182
Micron® CSC*	432
Fiberglass Bottomkote® NT	512
Interspeed 640	247
SeaVoyage®	286

At the end of the testing (January 2024), the paint system thickness values for each panel will be recorded again.

Photographs of panels – July 2023

For this report, pictures after the end of 6 months of testing (from the months of July and August 2023 only) are shared. For Anacortes, the pictures shared in this report are from August 2023 (5 months into the testing) and for all other locations, images are from July 2023. At the end of the year-long testing, a separate PDF file with images will be uploaded for the public. This PDF will contain all the images (912 in total) from all 12 months and all four locations.

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

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

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

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

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

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

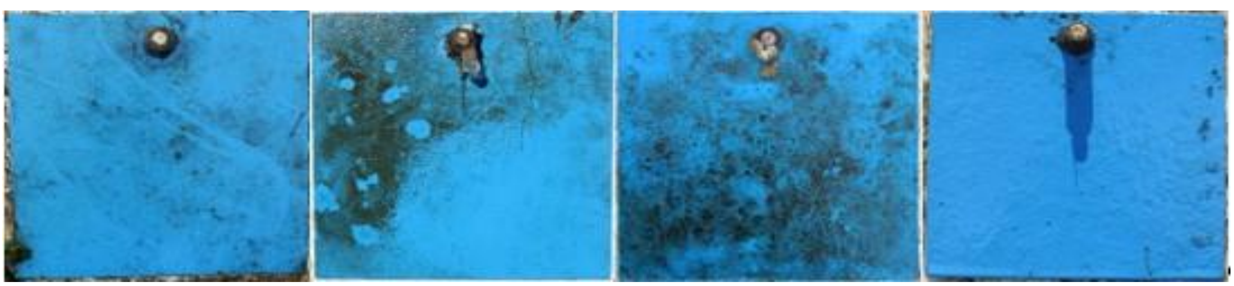

Figure 9: Shelter Island Plus™ – from Port Orchard, Gig Harbor, Anacortes, and Seattle (left to right).

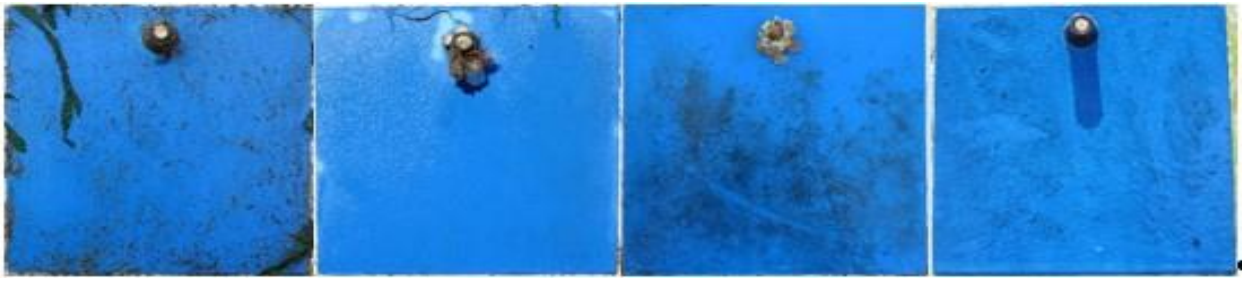

Figure 10: EP-ZO – from Port Orchard, Gig Harbor, Anacortes, and Seattle (left to right).

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

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

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

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

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

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

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

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

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

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

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

Typical fouling types in Puget Sound

Some of the typical marine fouling types found in the Puget Sound include barnacles, coelenterates, encrusting bryozoans (EB), hydroids, tunicates, filamentous bryozoans (FB), and algae.

ASTM antifouling performance evaluation

To evaluate the antifouling rating for each of the paints, mean values of F.R., A.F., A.C., and O.P. from three ocean water locations for each paint are added to Table 16.

Table 16: Mean fouling and ratings of antifouling paints from three ocean water locations.

Origin: ECOLOGY & WSU

Series: Performance Test

Base: Steel

Size: 9 inches x 9 inches

Place of immersion: Puget Sound, WA

Depth of immersion: 1.5 to 3.5 feet

Date immersed: January 21, 2023

Date inspected: July & August 2023

Test Surface PIN	Test Surface Paint	Fouling on Surfaces	Physical Condition	% Rating F.R.	% Rating A.F.	% Rating A.C	% Rating O.P.
19	SeaVoyage®	Barn: None Others: Al (45% in Gig Harbor and 15% in Anacortes)	Sea mud (60%, Port Orchard), Clear (G. Harbor) & Seaweed (35% from the rack, Anacortes)	77	100	100	77
1	Hydrocoat® ECO	Barn: None Others: Al (13%, Gig Harbor)	Sea Slime (SS) + mud (20%, Port Orchard), SS (80%, G. Harbor & 20%, Anacortes)	94	100	100	94
2	ECO HRT®	Barn: None Others: Al (20%, Gig Harbor & 5%, Anacortes)	Sea Slime (SS) + mud (99%, Port Orchard), SS (50%, G. Harbor) & Clear (Anacortes)	88	100	100	88
3	Micron CF	Barn: None Others: Inc. Al (? %, Port Orchard), Al (50%, Gig Harbor & 20%, Anacortes)	Sea Slime (SS) + mud (90%, Port Orchard), SS (80%, G. Harbor) & SS + soil (15%, Anacortes)	72	100	100	72
4	Pacifia Plus	Barn: None Others: Al (15%, Gig Harbor) & Inc. Al (20%,) & Al (2%, Anacortes)	Sea mud (25%, Port Orchard), Clear (G. Harbor) & SS (10%, Anacortes)	89	100	100	89
5	Smart Solution	Barn: None Others: Al (15%, Port Orchard; 20%, Gig Harbor & 60%, Anacortes)	SS + mud (25%, Port Orchard), Sea mud (7%, G. Harbor & 20%, Anacortes)	63	100	100	63
6	Shelter Island Plus™	Barn: None Others: Al (10%, Port Orchard; 35%, Gig Harbor & 50%, Anacortes)	Clear (Port Orchard), Sea mud (5%, G. Harbor & 30%, Anacortes)	63	100	100	63

Test Surface PIN	Test Surface Paint	Fouling on Surfaces	Physical Condition	% Rating F.R.	% Rating A.F.	% Rating A.C	% Rating O.P.
7	EP-ZO	Barn: None Others: Inc. Al (Port Orchard), Al (2%, Gig Harbor & 30%, Anacortes)	Sea mud (5%, Port Orchard), Clear (G. Harbor) & Sea mud (15%, Anacortes)	84	100	100	84
8	EP SN-1	Barn: Barn, 18 (3 to 13mm, Port Orchard) Others: Al (20%, Port Orchard; 55%, Gig Harbor & 30%, Anacortes)	Sea mud or Inc. Al (70%, Port Orchard), Clear (G. Harbor & Anacortes)	54	100	100	54
9	EP-2000	Barn: 6 (3 to 9 mm, Port Orchard); 2 (10 to 13 mm, Anacortes) Others: Al (15%, Anacortes)	Clear (Port Orchard, G. Harbor & Anacortes)	89	100	100	89
10	Intersleek® 1100 SR	Barn: None Others: Al (5%, Anacortes)	Clear (Port Orchard), SS + soil (30%, G. harbor), & soil (20%, Anacortes)	97	100	100	97
11	Propspeed®	Barn: 1 (10 mm, Anacortes) | CO: 1 (15mm, Gig Harbor) Others: Al (20%, Port Orchard; 5% Anacortes)	Clear (Port Orchard), SS + sand (35%, G. Harbor) & Clear (Anacortes)	86	100	100	86
12	CUKOTE	Barn: None Others: Al (15%, Port Orchard & Gig Harbor; 60%, Anacortes)	Inc. Al (20%, Port Orchard), Sea mud (20%, G. Harbor & Anacortes)	65	100	100	65

Test Surface PIN	Test Surface Paint	Fouling on Surfaces	Physical Condition	% Rating F.R.	% Rating A.F.	% Rating A.C	% Rating O.P.
13	AF 33	Barn: None Others: Inc. Al (?, Gig Harbor), Al (30%, Anacortes)	Clear (Port Orchard), SS + mud (85%, G. Harbor) & sea mud (25%, Anacortes)	88	100	100	88
14	Sharkskin™	Barn: None Others: Inc. Al (?, Gig Harbor), Al (60%, Anacortes)	SS (5%, Port Orchard), SS + mud (85%, G. Harbor) & sea mud (30%, Anacortes)	77	100	100	77
15	PCA Gold	Barn: 1 (10 mm, Port Orchard) Others: Al (4%, Port Orchard; 65%, Anacortes), Inc. Al (?, Gig Harbor)	SS (5%, Port Orchard), SS + mud (85%, G. Harbor) & sea mud (20%, Anacortes)	72	100	100	72
16	Micron® CSC*	Barn: 1 (10mm, Port Orchard) Others: Inc. Al (?, Gig Harbor), Al (70%, Anacortes)	Sea soil (5%, Port Orchard), SS + mud (85%, G. Harbor) & Sea mud (25%, Anacortes)	71	100	100	71
17	Fiberglass Bottomkote® NT	Barn: None Others: Al (20%, Port Orchard; 35%, Gig Harbor & 55%, Anacortes)	Sea mud (5%, Port Orchard), SS + mud (70%, G. Harbor) & sea mud (30%, Anacortes)	58	100	100	58
18	Interspeed 640	Barn: 1 (7mm, G. Harbor) Others: Al (30%, Port Orchard; 90%, G. Harbor & 70%, Anacortes)	Inc. Al, sea mud + soil (20%, Port Orchard), Inc. Al or mature Al? (90%, G. Harbor) & mud (25%, Anacortes)	31	100	100	31

Al: Algae, SS: Sea Slime, Inc.: Incipient, Barn: Barnacles, CO: Coelenterates

Question mark (?) indicates that the fouling and sea mud + slime are not easily distinguishable on those panels but will be separated at the end of testing using a gentle wash.

Discussion on fouling from ocean sites

By taking the mean of percent ratings for fouling, top and primer layers' conditions, and overall performance from all three ocean water locations, it is evident that some antifouling paints did very well. Such as PIN 10, Intersleek® 1100 SR, a non-biocidal and non-copper-based paint. In the above table, the fouling is reported as non-colonial forms first such as, barnacles and coelenterates, in numbers and their sizes, and then the colonial form like, algae, is reported. For some of the paints, there is a chance that most of the algae reported could be loosely adhered algae or sea mud, but it is reported as a mature form of algae. One example is PIN 18, Interspeed 640, at Gig Harbor. The benefit of the doubt is given to mature algae, after examining the photograph from the month of August which was 7 months into testing for this location. It is possible that in September, some of the algae may wash away with some water movement, but it looks like it will settle on the panel.

Similarly, there were some incipient barnacles on PIN 9, EP-2000, at the Port Orchard test site, that washed away by July 2023. No chipping of undercoats consisting of primer, tie coats, or peeling of topcoats was observed for any of the panels on any test site after 6 months of testing. Therefore, all received a rating of 100 for A.C. and A.F.

Table 17 reports antifouling ratings for panels from the only lake water test site in Seattle, located in the west. The rating values in Table 17 aren't the mean values since there is only one lake water site. The need to develop a separate table for the lake water site is necessary as the water chemistry is quite different and the results should not be mixed with the ocean water sites.

Table 17: Reporting fouling and ratings of antifouling paints from the lake water location.

Origin: ECOLOGY & WSU

Series: Performance Test

Base: Steel

Size: 9 inches x 9 inches

Place of immersion: Puget Sound, WA

Depth of immersion: 1.5 to 3.5 feet

Date immersed: January 22, 2023

Date inspected: July 2023

Test Surface PIN	Test Surface Paint	Fouling on Surface	Physical Condition	% Rating F.R.	% Rating A.F.	% Rating A.C.	% Rating O.P.
19	SeaVoyage®	Barn: None Others: NF	SS (80%)	100	100	100	100
1	Hydrocoat® ECO	Barn: None Others: Inc. Al (40%) NF	SS + mud (40%)	100	100	100	100
2	ECO HRT®	Barn: None Others: Al (20%)	SS + mud 45%)	75	100	100	75
3	Micron CF	Barn: None Others: NF	SS + seaweed (95%)	100	100	100	100
4	Pacifia Plus	Barn: None Others: NF	SS + seaweed (95%)	100	100	100	100

Test Surface PIN	Test Surface Paint	Fouling on Surface	Physical Condition	% Rating F.R.	% Rating A.F.	% Rating A.C.	% Rating O.P.
5	Smart Solution	Barn: None Others: NF	Clear	100	100	100	100
6	Shelter Island PlusTM	Barn: None Others: NF	Clear	100	100	100	100
7	EP-ZO	Barn: None Others: Inc. Al (15%) NF	Clear	100	100	100	100
8	SN-1	Barn: None Others: NF	SS (75%)	100	100	100	100
9	EP-2000	Barn: None Others: NF	Clear	100	100	100	100
10	Intersleek® 1100 SR	Barn: None Others: NF	Sea mud (5%)	100	100	100	100
11	Propspeed®	Barn: None Others: Al (20%)	Clear	75	100	100	75
12	CUKOTE	Barn: None Others: NF	SS + seaweed (95%)	100	100	100	100

Test Surface PIN	Test Surface Paint	Fouling on Surface	Physical Condition	% Rating F.R.	% Rating A.F.	% Rating A.C.	% Rating O.P.
13	AF 33	Barn: None Others: NF	SS+ sea mud (95%)	100	100	100	100
14	SharkskinTM	Barn: None Others: NF	SS + sea mud (85%)	100	100	100	100
15	PCA Gold	Barn: None Others: NF	SS + sea mud (85%)	100	100	100	100
16	Micron® CSC*	Barn: None Others: NF	SS + sea mud (95%)	100	100	100	100
17	Fiberglass Bottomkote® NT	Barn: None Others: Inc. Al (15%) NF	SS + mud (45%)	100	100	100	100
18	Interspeed 640	Barn: None Others: NF	Sea mud (40%)	100	100	100	100

Al: algae, NF: no fouling, SS: sea slim, Inc.: incipient, barn: barnacles

Discussion on fouling from the lake water site

Antifouling paints are doing better in lake water in terms of fouling resistance and physical condition. No visible destruction of the top and primer layer can be seen either on any of the panels at the Seattle test site after 6 months of submergence.

Conclusions

Results from Table 16 indicate that after five to six months of testing in ocean water, the top five antifouling paints in order are:

(1) Intersleek® 1100 SR
(2) Hydrocoat® ECO
(3) Pacifia Plus & EP- 2000
(4) ECO HRT® & AF 33
(5) Propspeed®

Apart from AF 33, the top five choices are non-copper paints. For lake water, apart from two paints, Propspeed® and ECO HRT®, all others received a 100 O.P. rating.

Results from the ASTM standard method tell us to use control paint, in this case SeaVoyage ®, as the standard paint, and rate test paints or panels according to that. For instance, if PIN 19 received an O.P. of 77 in ocean water, the highest rating of test paints should be 77 and not 100.

In this study, we are comparing the performance of each paint with the control panel paint. Note that SeaVoyage® is a US-Navy-approved paint and is not easily available to the public. It was selected from the qualified product list (QPL) of Navy antifouling paints and was replaced with the lead-based paint mentioned in the ASTM standard after discussing it with the ASTM committee.

For the final report, before being rated, the panels will be gently washed with tap water to remove any loosely adhered sea mud, slime, or weed. This will eliminate any doubts about the incipient fouling, especially algae, occurring on the panels.

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Appendix B: Acronyms and Abbreviations

Table 18: Acronyms, abbreviations, and definitions

Term	Definition
A.C.	Anticorrosive film
A.F.	Antifouling film
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Material
BM-1	Benchmark 1
$BM\text{-}1^{TP}$	The subscript means the transformation products drive BM score
BM-2	Benchmark 2
BM-3	Benchmark 3
BM-4	Benchmark 4
BMPs	Best Management Practices
BPR	Biocidal Products Regulation
BYGP	Boatyard General Permit
CHA	Chemical Hazard Assessment
COC	Chemical of Concern
Cu_2O	Cuprous Oxide
CUOCU	Cupric oxide
CuSCN	Cuprous Thiocyanate
DCOIT	Dichlorooctylisothiazolinone
Ecology	Washington Department of Ecology
ECONEA	Tralopyril
EPA	Environmental Protection Agency
EU	European Union
EU BPR	European Union Biocidal Products Registration
F.R.	Fouling resistance
FIFRA	Federal Insecticide, Fungicide, and Rodenticide Act
FRCs	Foul Release Coatings

Term	Definition
HDPE	High density polyethylene
O.P.	Overall performance
OECD	Organization for Economic Cooperation and Development
OEM	Original equipment manufacturer
PCA	Principal component analysis
PDMS	Polydimethylsiloxane
PFAS	Per and polyfluoroalkyl substances
PICOL	Washington State University Pesticide Information Center Online Database
PIN	Panel identification number
POTW	Publicly owned treatment works
PP	Polypropylene
PPG	PPG Industries
QAPP	Qualified Assurance Project Plan
SCIL	EPA Safer Chemicals Ingredients List
SPCs	Self-polishing coatings
SWPP	Stormwater Pollution Prevention Plan
SYC	Seattle Yacht Club
TBT	Tributyltin
TDS	Technical Data Sheet
Term	Definition
USA	United States of America
UV	Ultraviolet light
VGP	Vessel General Permit
VIDA	Vessel Incidental Discharge Act
WSDA	Washington State Department of Agriculture
WSU	Washington State University