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Biofouling in Practice: A Study of the Impacts and Industry Management Practices

Petter Korslund, Jotun, Sandefjord/Norway, petter.korslund@jotun.com
Morten Sten Johansen, Jotun, Sandefjord/Norway, morten.sten.johansen@jotun.com

Abstract

To develop a global picture of biofouling management and related impacts, Jotun carried out an industry report including answers from 1000 ship owners and operators. The report investigates the hidden costs of existing knowledge gaps across regulatory penalties, fuel inefficiencies and environmental risks. This paper summarizes the report.

1. Introduction

Biofouling management refers to the strategies and technologies used to control and prevent the accumulation of marine organisms such as algae, barnacles, molluscs, and bacteria on submerged surfaces like ship hulls. This accumulation begins rapidly once a vessel enters the water and can significantly reduce vessel efficiency by increasing fuel consumption and maintenance costs.

Beyond operational impacts, unmanaged biofouling also poses environmental risks by facilitating the global spread of invasive aquatic species, which can disrupt marine ecosystems and threaten biodiversity. The International Maritime Organization (IMO) updated its Biofouling Guidelines in 2023, emphasising a globally consistent approach that integrates best practices for hull cleaning, antifouling system selection, and ship design, to minimise both the emissions that result from increased fuel consumption and the transfer of invasive species. This was supplemented with guidance on in-water cleaning of ships in April 2025.

In April 2025, the IMO's Marine Environment Protection Committee (MEPC) member states also agreed to develop a legally binding global framework for biofouling management. While this will not become an international requirement for a number of years, the industry must begin its preparations in earnest. This regulatory momentum is reinforced by parallel developments in emissions control. The full application of the FuelEU Maritime Regulation from January 2025 and the phased inclusion of shipping in the EU Emissions Trading System (EU ETS) are tightening requirements on greenhouse gas intensity and emissions reporting for ships operating in European waters. Amendments to European regulations on air pollution from ships are on the horizon, with further revisions expected in October 2025 to address fuel standards and emissions data collection.

Effective biofouling management is therefore essential not only for maintaining vessel performance and reducing greenhouse gas emissions, but also for protecting marine environments and ensuring compliance with evolving international regulations. Its effectiveness on these matters should not be understated. DNV Maritime Advisory verified that vessels coated by Jotun avoided 11.1 million tons CO_2 emissions in 2024 as a result of the antifouling used. This is equivalent to nearly 30% of the country of Norway's total CO_2 emissions for one year.

Despite these international efforts, there remains a significant gap in national-level preparedness. The 2023 IPBES report revealed that only a minority of countries have enacted laws or invested in measures to address biofouling's role in the spread of invasive species, underscoring the need for harmonised global action and industry readiness to meet forthcoming requirements. As the IMO moves toward a legally binding global framework for biofouling management, the industry faces a pivotal transition. Proactive adoption of best practices will be essential not only for regulatory compliance but also for operational efficiency and environmental leadership. The following report presents new research commissioned to inform how the industry can best prepare for this new era of biofouling management.

2. Methodology & Key results

To develop a global picture of biofouling management, Jotun carried out research exploring the attitudes of ship owners and operators to different strategies. The research was conducted by Censuswide, https://www.censuswide.com, among a sample of 1000 ship owners and operators across 11 countries, Table I, between 3 and 10 April 2025.

Table I: Composition of responding survey participants

Africa	9%	Middle East	15%
Asia Pacific	21%	North & Central America	18%
China	12%	South America	12%
Europe	33%	South Asia	15%

The survey revealed that biofouling management has a broad level of awareness already, as over three-quarters of ship owners and operators (79%) considered hull performance a top priority for their company. However, only 31% thought their company had adequate knowledge of available hull performance solutions, uncovering a knowledge gap between what is considered important and understanding of strategies and solutions. The research also revealed that 1 in 10 ship owners and operators (12%) are not confident in their own knowledge of biofouling. Despite this, 54.2% said that they do plan routes to minimise biofouling risk, demonstrating that biofouling is a key consideration in daily operations for the shipping industry.

The report set out the hidden costs of existing knowledge gaps on ship owners and operators across regulatory penalties, fuel inefficiencies and environmental risk, for example:

- 2 in 5 (41%) ship owners and operators have faced regulatory penalties because of biofouling related issues.
- 2 in 5 (38%) ship owners and operators have been refused access to ports as a result of biofouling related issues.
- Almost half (49%) of ship owners and operators said they avoid ports with stringent biofouling regulations.
- 50.4% of ship owners and operators have experienced increased fuel inefficiencies as a result of poor biofouling management.
- 1 in 5 (21%) are not using the most effective antifouling paint for each vessel in their fleet based on its biofouling management needs.

Overall, this research uncovered several industry trends in biofouling management, from identifying where knowledge gaps exist to exposing the hidden risks of poor strategies. The sector stands to see huge benefits from closing knowledge gaps on biofouling management. Taking into consideration the proposed changes to regulation and upcoming milestones, this report sets out a roadmap for rethinking biofouling as a strategic maritime priority.

3. Impact of regulatory non-compliance

Although the implementation of globally aligned regulations on biofouling is an ongoing discussion, some regions have already implemented strict regulations to help reduce the spread of invasive aquatic species. This is particularly true in the APAC region, with New Zealand and Australia having put in place mandatory regulations since 2018 and 2022 respectively.

These regulations have marked a significant shift to enforceable standards, with vessels required to demonstrate biofouling management through hull cleaning, maintenance records, or approved risk management plans. To make effective decisions on biofouling management plans, ship owners and operators must consider several factors such as vessel type, routing, and marine environments. The risks of not meeting them threaten substantial effects in their global operations.

Regulatory penalties or refused access to ports can have a significant impact, namely delays and direct financial burdens.

However, a unified approach to biofouling, with standardised requirements, is not enough to ensure vessels are not penalised due to their biofouling activities, as these requirements can only set the goal, and not the "how to". This must also be paired with improved knowledge and proactive planning, so they are not restricted in the short term or subject to penalties when a binding IMO framework is introduced.

Stricter biofouling regulations in regions like New Zealand and Australia signal a global shift toward enforceable standards. The penalties and port refusals already faced by many ship owners show that avoiding regulated ports is no longer sustainable. Acting now will help ship owners avoid costly disruptions and meet future regulations in an increasingly regulated environment.

4. Impact of decreased fuel efficiency

If a ship has high levels of biofouling, the accumulation of organisms on a hull increases drag, causing the vessel to use more fuel and increasing costs to the operator. The survey results found that 50.4% of ship owners and operators have experienced increased fuel inefficiencies as a result of poor biofouling management. In an environment where profit margins are increasingly tight, this can have a severe impact on a ship owner's bottom line.

Of the survey respondents, 59.5% said cost-effectiveness is more important than environmental impact when choosing antifouling paints and these results reveal industry has not yet fully embraced the opportunity that biofouling technologies present. Clean hulls mean improved fuel efficiency, delivering a return on investment over time, as well as a reduced environmental impact, indicating a significant gap in industry knowledge over what these technologies can do.

However, survey data also suggests that the implementation of fuel efficiency regulations by the IMO may be improving awareness. With the use of low-carbon alternative fuels still in relative infancy, ensuring that traditional fuels are utilised in the most efficient way possible is key to reducing penalties.

In addition to this, with alternative fuels having a higher price point, ship owners that are embracing these fuels as part of their decarbonisation strategy can also benefit from increased profitability through enhanced fuel efficiency that is delivered by improved hull performance.

Table II: "We consider hull performance management an important factor in compliance with IMO fuel efficiency regulations"

Agree (net)	77.10%
Strongly agree	37.00%
Somewhat agree	40.10%
Neither agree nor disagree	16.60%
Somewhat disagree	4.20%
Strongly disagree	1.30%
Disagree (net)	5.50%
N/A	0.80%

Over three-quarters of those surveyed (77%), Table II, consider hull performance management an important factor in compliance with IMO fuel efficiency requirements. These findings underscore a growing recognition within the industry of the direct link between effective biofouling management and efficiency. The adoption of advanced biofouling management can significantly reduce speed loss and fuel consumption, translating into measurable cost savings over a vessel's operational life.

While the initial investment in biofouling management technologies or services may seem significant, the long-term benefits far outweigh the costs. As the sector continues to adapt to stricter environmental standards, those who prioritise biofouling management will not only achieve compliance more efficiently but will also gain a competitive edge through enhanced operational efficiency and sustainability.

5. Approach to support environmental targets

Today there are a range of antifouling coatings available, but the effectiveness of each is dependent on the marine environment the vessels are exposed to. Taking a more nuanced approach that is appropriate for the environment of operation will help ship owners and operators to maximise effectiveness.

However, as many as 1 in 5 (21%), Table III, are aware that they are not using the most effective antifouling paint for each vessel in their fleet. This reveals a broader issue within the industry, suggesting that biofouling is still not fully prioritised despite global trends shifting to stricter environmental practices.

Table III: "We choose the most effective antifouling paint for each vessel in our fleet based on its biofouling management needs"

Agree (net)	46.90%
Strongly agree	23.26%
Somewhat agree	23.64%
Neither agree nor disagree	32.17%
Somewhat disagree	13.76%
Strongly disagree	7.17%
Disagree (net)	20.93%

Nearly 2 in 5 ship owners and operators surveyed (37%), Table IV, are taking a one-size-fits-all approach to antifouling coatings by using the same coating across their entire fleet. This is despite many operating vessels in different marine environments. When considering the use of biofouling mechanisms in different environments, the Sustainable Shipping Initiative's Ram Ganesh Kamatham said, "The operating environment of the ocean is vast, so any ship owner's starting point in biofouling management should be understanding regional specifics such as varied temperatures, marine protected areas, and other ecologically sensitive areas. So, it's not about using any one specific technology, but it is important to have a ship-specific biofouling management plan in place."

Table IV: "We use the same antifouling paint across the entire fleet"

Agree (net)	37.21%
Strongly agree	16.67%
Somewhat agree	20.54%
Neither agree nor disagree	31.20%
Somewhat disagree	19.19%
Strongly disagree	12.40%
Disagree (net)	31.59%

Considering various environments and different trade patterns demand different requirements to avoid biofouling, this is a concerning and shortsighted approach to biofouling management that may result in a larger impact on the marine environment.

Coatings that contain active ingredients (also referred to as biocides) can be effective for controlling biofouling, depending on trade patterns and the environment of operation, and are an indispensable asset for maritime efficiency and emissions control. Yet, data suggest that the overall industry focus is still on cutting carbon emissions rather than on meeting the full range of all ESG targets.

This is also demonstrated by the survey results, which reveal that two-thirds (66%) of ship owners and operators say that antifouling solutions with active ingredients are more effective than paints without these ingredients. A similar number of respondents (69%) are not prioritising reducing the use of active ingredients when choosing emission reduction technologies.

With the preservation of marine biodiversity an increasingly important ESG target for both governments and industry, there is growing pressure on ship owners and operators to demonstrate an understanding of the options available. Choosing the right solution for the right environment is therefore key to meeting these targets and limiting biofouling, to protect marine environments and avoid the transfer of aquatic invasive species.

6. Setting a course for compliance

With the IMO's 2023 guidelines as a foundation, forthcoming regulations are expected to mandate that all ships maintain a dedicated Biofouling Management Plan (BFMP) and a Biofouling Record Book (BFRB), outlining clear procedures for inspection, cleaning, and ongoing maintenance.

Encouragingly, 78% of ship owners and operators report that each ship in their fleet already has a bio-fouling management plan. However, closer inspection suggests there is significant room for improvement. For example, just 40% said they have a proactive monitoring plan for biofouling in place for each vessel in their fleet. In addition to this, when planning their journeys, 49% of those surveyed said they avoid ports with stringent biofouling regulations.

Multiple regulatory standards can create challenges for fleets. As the shipping industry continues on the path towards a global framework, we encourage the implementation of tailored systems that take into consideration factors like routes, time for cleaning and the environment of operation. This will help to navigate the here and now and the changes on the horizon.

Stricter port entry requirements, like those already enforced in New Zealand and Australia, are likely to become more common globally, even before international regulations are finalised. Additionally, global standards like the ISO/DIS 6319, which details the best practices for in-water cleaning, signal yet more movement towards aligned international approaches.

A mandatory, standardised system for biofouling management would bring much-needed consistency to biofouling management, improving compliance and environmental outcomes, and reduce the adoption of non-viable practices to avoid biofouling management techniques.

7. Conclusion

As global regulations tighten and environmental expectations rise, effective biofouling management is becoming essential for the shipping industry. Stricter rules in regions like New Zealand and Australia signal a wider move toward enforceable standards, with penalties and port refusals already impacting many operators. Proactive investment in tailored biofouling management, though initially costly, delivers long-term savings. Closing the gap between ESG ambitions and current practices by tailoring solutions to fleet will not only improve operational efficiency but also support sustainability and future growth in an increasingly regulated shipping industry. By acting now, ship owners can avoid costly disruptions and demonstrate leadership. Ultimately, those who embrace proactive, tailored biofouling management will be best positioned to thrive, ensuring both compliance and commercial success in a more sustainable maritime future.

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Port Requirements to In-Water Cleaning and Development of a Test Method

Jørn-Erik Hausmann, Port of Bergen, Bergen/Norway, jorn.hausmann@bergenhavn.no
Tone Knudsen Fiskeseth, DNV, Høvik/Norway, tone.knudsen.fiskeseth@dnv.com

Abstract

The Port of Bergen and the Port of Oslo have implemented a ban on hull cleaning unless the equipment used is pre-approved and includes capture. This decision was made due to observed pollution from hull cleaning in their port sediments and the invasion of alien species, such as Seavomit (Didemnum vexillum). In 2023, DNV was commissioned by the Port of Bergen and the Port of Oslo to develop a test procedure for the approval of hull cleaning equipment. To facilitate the implementation of this approval procedure, a hull cleaning pilot was launched in March 2025 under the Green Shipping Programme in Norway. Led by the Port of Bergen, the pilot aims to refine the procedure into a practical method for both ex-situ and in-situ testing. The pilot will adhere to guidance and defined limit values as outlined in the IMO guidance for in-water cleaning (MEPC.1-Circ.918), and will also follow the principles of ISO 20679 for in-situ testing. The pilot will specifically examine the biological aspects in an ex-situ test setup, while also exploring opportunities to use sensor technology for monitoring the cleaning process. The primary objective of the pilot study is to provide Norwegian ports, cleaning providers, and government authorities with guidance for testing, emphasizing the reduction of released organisms, biocides, and microplastics into the sea.

1. Introduction

In 2023, the Ports of Bergen and Oslo banned hull cleaning unless the equipment effectively captured debris. This year (2025), the Maritime Authority in Norway issued draft requirements for all ships entering Norwegian waters, as well as for all vessels conducting in-water cleaning activities within Norwegian territorial waters, https://www.sdir.no/contentassets/9acc75d5a477489785df7de2afdd850a/proposed-regulations-of-on-the-management-of-hull-biofouling-.pdf. When final and after 1 July 2028, any such cleaning activities must employ the best available technology. By this deadline, cleaning service providers are expected to enhance their technologies in accordance with the Maritime Authority's criteria, as specified below.

In addition to the national draft requirements, a hull cleaning pilot project was launched in March 2025 under the auspices of the Green Shipping Programme in Norway, https://greenshippingprogramme.com/pilot/in-water-cleaning-with-capture/. This initiative, led by the Port of Bergen with facilitation provided by DNV, includes numerous Norwegian stakeholders such as ship owners, cleaning service providers, laboratories, and government representatives. The objective of the pilot is to develop a practical guide for both ex-situ and in-situ testing of in-water cleaning equipment.

Initially, the pilot will adopt a test procedure developed by DNV in 2023 on behalf of the Ports of Oslo and Bergen. The pilot will adhere to the guidelines and defined limit values presented in the *IMO (2025)* guidance for in-water cleaning, alongside the principles outlined in *ISO (2025)* for in-situ testing. Specifically, the pilot seeks to investigate the biological aspects within a controlled test environment. While the IMO guidance has established performance criteria relative to ambient background levels, it does not detail methods for measuring the effective capture of biofouling organisms. The pilot aims to explore methodologies for testing and potentially quantifying capture capacity under optimal conditions within a closed (ex-situ) setup.

2. Approval process

2.1. Port procedure for Approval (delegated to class Societies)

An ex-situ test aims to demonstrate in-water capture of dislodged materials associated with the cleaning of an underwater surface, while an in-situ test aims to demonstrate in-water cleaning in a full-scale environment while preventing residual waste substances being returning into the aquatic environment, Fig.1.

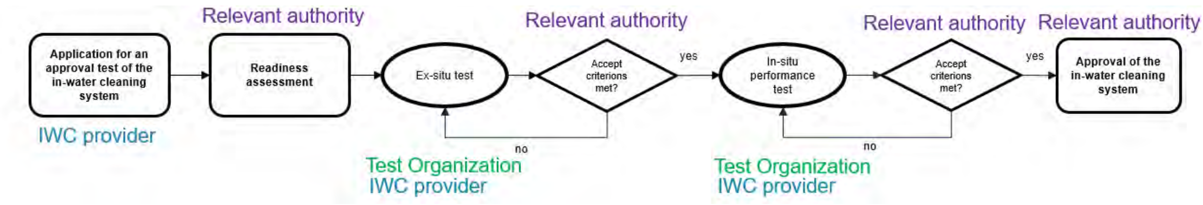

Fig.1: Illustration of an approval process

2.2. Performance Criteria

IMO has recognized that there is not yet sufficient scientific evidence and global consensus to set discharge standards for waste substances based on specific concentrations. A complete capture and/or no impact on the coating is not technologically achievable. IMO have therefore adopted a statistical approach whereby concentrations of each substance near the cleaning unit and in any cleaning system effluent should not be significantly increased relative to ambient levels.

The Norwegian draft legislations suggest in-water cleaning to be performed with the best available technology. In considering what constitutes the best available technology, particular consideration shall be given to:

a. the greatest possible limitation of pollution arising from the cleaning;
b. the maximum reduction in the release of living organisms;
c. the effective removal of hull biofouling;
d. the minimization of damage and degradation to the anti-fouling system;
e. the highest possible capture rate of material released during hull cleaning.

For the Port of Bergen, the performance of an in-water cleaning system_shall meet the above expectations by using tested and approved cleaning equipment with capture. A cleaning equipment without capture may be used if the coating does not release waste substances during cleaning and if it can be justified that an equipment will not clean any area that contain macrofouling or non-native organisms.

2.3. Ex-situ testing

The IMO Guidance suggests that the relevant authority should assess the readiness of the in-water cleaning system for in-situ testing, based on documentation, including the results of ex-situ tests. However, the Guidance does not prescribe how ex-situ testing shall be performed, neither is it provided in the ISO standard for testing of in-water cleaning, *ISO (2025)*.

The pilot led by Port of Bergen will explore ex-situ testing methods. The goal is to show how a system can capture dislodged biofouling during in-water cleaning and manage biofouling materials and wastewater according to discharge criteria.

The ex-situ test set-up will employ test plates with naturally grown biofouling, ensuring consistent growth across multiple plates. The test tanks will contain clean water specifically prepared to demonstrate capture efficiency. Figs.2 and 3 illustrate the principle of an ex-situ test environment: the test plates and the in-water cleaning system are submerged in the test tank, and the captured materials and seawater form an influent transported to the separation and treatment unit before the effluent is discharged to the sea.

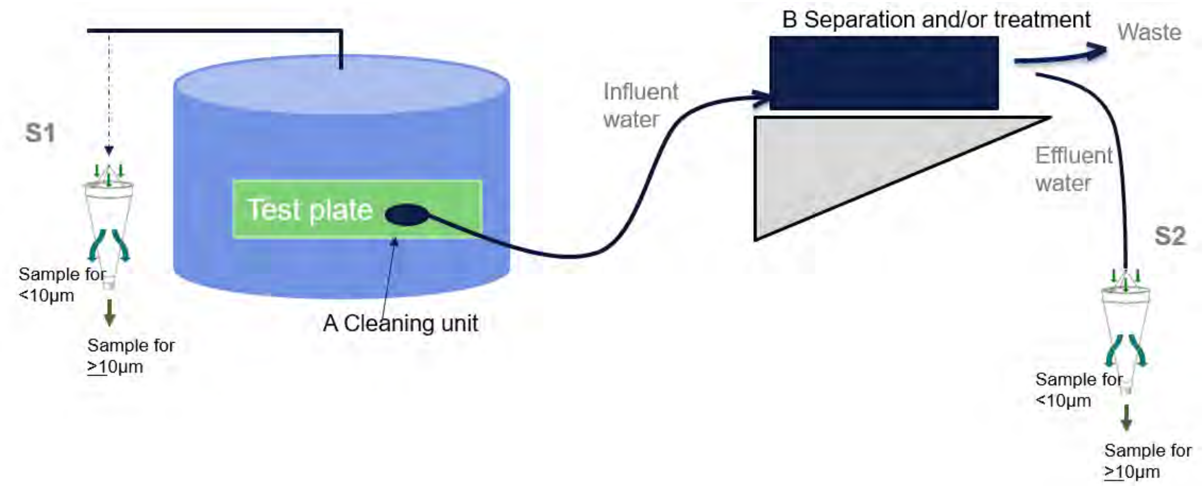

Fig.2: Ex-situ test set-up of an in-water cleaning unit, with background sampling of clean water (S1) and effluent water (S2)

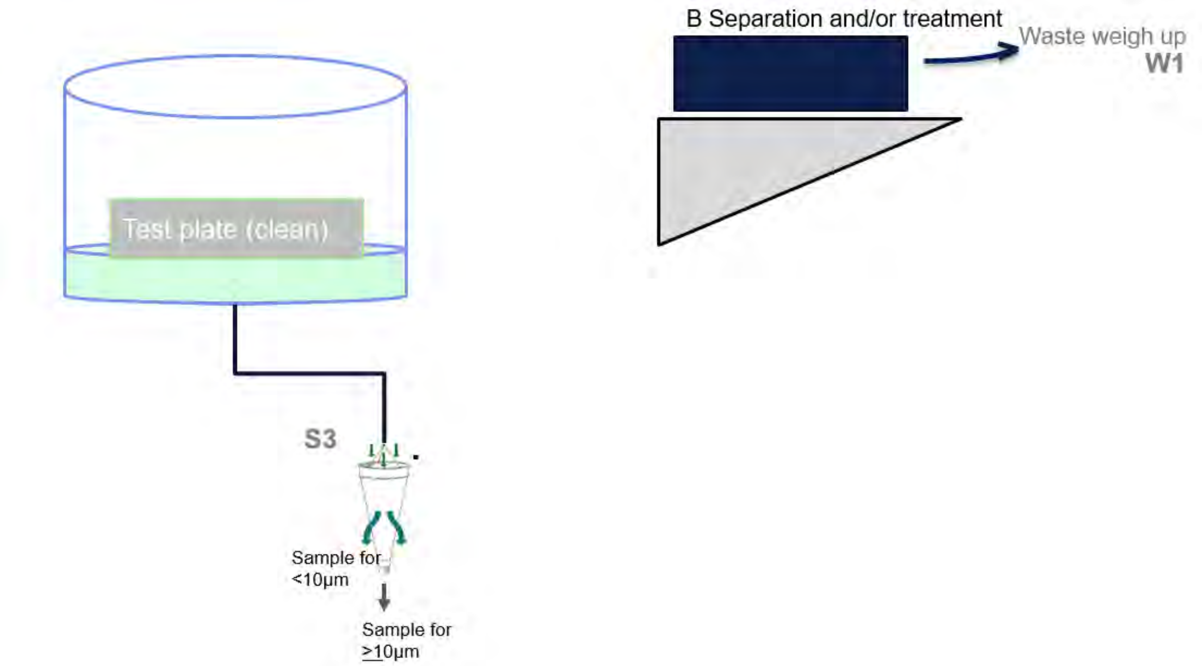

Fig.3: Ex-situ test set-up of sample after cleaning (S3) to measure what has not been captured and weight measurement of captured waste (W1)

2.4. In-situ testing

The in-situ testing will follow the principles outlined in MEPC.1/Circ.918, which emphasize the importance of assessing the environmental impact and effectiveness of the in-water cleaning system in real-world conditions. The experimental setup for in-situ testing will follow these specific requirements:

- Testing must be conducted on at least three different ships, with various coating types, biofouling levels, and environmental conditions.
- Each test should have a minimum duration of 90 minutes (30 minutes for niche area)
- Water quality parameters must be monitored before and after cleaning
- The system's ability to capture and manage dislodged biofouling materials and wastewater must be verified

The measurements taken should ensure that the cleaning process does not adversely affect the marine environment, adhering to the guidelines provided in MEPC.78(80). The sampling and analysis methodology as provided in ISO standard 20679 will be used when designing in-water cleaning tests.

The pilot will explore how to practically perform an in-situ test of cleaning a niche area but also a large hull area. By studying approaches for sampling, the group should find a methodology to be used during cleaning of both these situations. The samples shall be used to see the relevance of analyzing particles, particle distribution, metals, plastics and live organisms.

3. Discussion

An ex-situ test will ensure fair, controlled, replicative and documented test conditions for the service providers, but it is somehow difficult to mirror real challenging conditions. In-situ test will represent full-scale real condition cleaning, but the background concentrations of particles and biology will vary depending on currents, waves and therefore we predict difficulties to obtain representative water samples.

Pilot testing may not cover all aspects but should lead to the drafting of a Guidance for Testing of in-water cleaning equipment with capture. Our main goal for the Guidance is to suggest ways to conduct ex-situ testing and provide an overview of representative samples that should be taken during ex-situ and in-situ testing. The experimental set-up should be designed in a way that can challenge the cleaning equipment within its specifications.

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Evaluating Ultrasonic Antifouling Technology: Effectiveness Against Biofouling and Potential Impact on Marine Mammals

Micaela Machado Querido, DHI A/S, Hørsholm/Denmark, miqu@dhigroup.com
Pernille Bohn, DHI A/S, Hørsholm/Denmark, pebo@dhigroup.com
Torben Madsen, DHI A/S, Hørsholm/Denmark, toma@dhigroup.com
Rémi Maguet, DHI A/S, Hørsholm/Denmark, rema@dhigroup.com

Abstract

Ultrasonic transducers hold potential to protect some of the areas on vessels which might be difficult to protect with other antifouling technologies, while reducing the chemical pressure on the environment. However, these systems introduce underwater radiated noise that may pose risks to marine fauna. This study evaluated the sound propagation from ultrasonic transducers installed on two vessels and assessed potential impacts on cetaceans by comparing sound levels with known hearing sensitivities. Results suggest that ultrasonic transducers may impact mammals causing behavioural disturbances or hearing effects, raising concerns about underwater noise as an emerging environmental stressor.

1. Introduction

Biofouling on ships may lead to major economic costs, due to increased fuel consumption, decreased speed or damages to parts of the vessel relying on free flow of water. Greenhouse gas emissions of shipping, including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), expressed as CO_2 equivalents, have increased from 977 million tonnes in 2012 to 1,076 million tonnes in 2018. The total emissions from shipping contribute by ~3% of the global emissions of greenhouse gases, *IMO (2021)*.

Furthermore, the transfer of non-indigenous species can lead to biodiversity loss and disruption of ecosystems. When transported to regions beyond their native range, these species may become invasive, threatening biodiversity and disrupting ecological balance.

Antifouling coating is the most widespread method to prevent biofouling. While effective in reducing fouling, these coatings release toxic chemicals into the marine environment, contributing to pollution and posing risks to aquatic life. In response to growing environmental regulations and sustainability concerns, alternative antifouling technologies are being explored. Among these, ultrasonic antifouling systems offer a promising, non-chemical method for preventing biofouling on ships.

Ultrasonic antifouling devices produce sound waves that induce micro-vibrations in the ship's metal structures, interfering with the ability of organisms to attach and colonize surfaces. This method can be used together with traditional antifouling coatings and one of the main advantages is the installation in niche areas of vessels, that often difficult to protect by other antifouling technologies.

The characteristics of system design, such as frequency range, power output, number and location of the transducers can influence not only their effectiveness in preventing biofouling, but also the extent of underwater radiated noise they produce.

Commercial shipping is a major contributor to underwater radiated noise which is known to cause adverse effects on marine animals including mammals, fish and invertebrates. The impact of underwater noise on marine life is an area of increasing environmental importance, *UN (2018), IMO (2024)*. Underwater noise generated by ships is typically associated with propellers, hull form, onboard machinery, wake flow, and operational and maintenance activities, *IMO (2024)*. The underwater noise emitted by ultrasonic antifouling systems may affect marine mammals such as whales, *Trickey et al. (2022)*, especially if the frequency of the system overlaps with the area of best hearing of the species, Table I. The impacts on marine mammals may comprise behavioural responses to the emitted noise or more severe hearing impairment.

The objective of this study was to evaluate the potential environmental side effects related to the underwater sound emitted from the ultrasonic antifouling systems installed onboard a crude oil tanker and a diving vessel.

2. Methodology

2.1. Measurements of underwater sounds

This study evaluated the underwater noise generated by ultrasonic antifouling systems installed on two vessels, a crude oil tanker and a diving vessel (catamaran), using a combination of field measurements and acoustic propagation modelling. The systems included ultrasonic transducers operating in the 20–40 kHz frequency range.

On the crude oil tanker, 34 transducers were installed across multiple seawater intake and cooling components. These included the high and low sea chests, strainer pipes, central freshwater coolers, vacuum condensers, and inner hull, as well as the propeller shaft. The system's electrochemical antifouling components were deactivated to isolate ultrasonic effects. On the diving vessel, four transducers were installed symmetrically along the inner surfaces of the port-side hull.

Underwater sound measurements were conducted in the Singapore Strait to characterise source levels and validate propagation models. A SoundTrap ST600 HF hydrophone recorder was deployed from a stationary survey vessel at varying distances from each source. For the oil tanker, data were collected while the vessel was anchored with its engine off, capturing sound pressure levels (SPL) at radial distances from 50 m to 1000 m at a fixed depth of 5 m. For the diving vessel, recordings were made with the ultrasonic system active and the engine off, at distances from 20 m to 1800 m and depths of 2 m and 5 m. Multiple configurations were tested to distinguish the contribution of transducers from other onboard systems.

Recorded sound data were analysed using time-frequency spectrograms to identify ultrasonic emission signatures and to compute SPLs in one-third octave bands. These empirical data informed the calibration of numerical models.

2.2. Modeling of underwater sound propagation

Sound propagation modelling was conducted using the MIKE Underwater Acoustic Simulator (MIKE UAS) developed by DHI. The model accounted for frequency-dependent sound attenuation, site-specific bathymetry, and seabed characteristics. The sound propagation models were calculated based on two geographic locations, the Singapore strait and Skagerrak strait (close do Denmark).

The model output included spatial maps of SPL and cumulative SEL, which were evaluated against cetacean impact thresholds defined by *Southall et al. (2019)*.

Two exposure scenarios were simulated: a static vessel (assuming 15 minutes of constant exposure) and a moving vessel (a vessel passing by a static animal at constant speed), to estimate the zones of potential behavioural disruption and auditory risk for different marine mammal hearing groups, Table I.

Table I: Generalized hearing ranges for marine mammal hearing groups

Hearing group	Generalized hearing range *
Low-frequency cetaceans (e.g., humpback whale)	7 Hz to 35 kHz
High-frequency cetaceans (e.g., killer whale)	150 Hz to 160 kHz
Very high-frequency cetaceans (e.g., harbour porpoise)	275 Hz to 160 kHz

Note: * Generalized hearing range for the entire group including all species within the group. Individual species' hearing ranges are typically not as broad; for details, see *Southall et al. (2007)*. Reference: *NMFS (2024)*.

3. Results

The propagation of underwater noise emitted from ultrasonic antifouling transducers installed on the oil tanker and the diving vessel was modelled using centre frequencies in the range of 20 to 40 kHz. These were compared against in-situ measurements conducted in the Singapore Strait. The SPLs centred at 31.5 kHz showed good agreement between modelled and measured data, considering uncertainties related to seabed composition and measurement locations.

Modelled SPLs were assessed against behavioural impact thresholds for low-, high-, and very high-frequency cetaceans. These thresholds, as outlined in *Southall et al. (2019),* were used to predict the spatial extent of behavioural responses. For the oil tanker, behavioural responses of low- and high-frequency cetaceans were predicted within 230 m in the Singapore Strait and up to 410 m in the Skagerrak. For very high-frequency cetaceans, such as harbour porpoise (Phocoena phocoena), the potential range of behavioural response extended to 3075 m in the Singapore Strait and 3210 m in the Skagerrak, Table II.

For the diving vessel, with fewer transducers and lower source levels, the ranges of behavioural reactions were significantly smaller. For low- and high-frequency cetaceans, behavioural reactions were predicted within 65 m, and for harbour porpoise within 1725 m.

Assessments of hearing impairment, including temporary threshold shift (TTS) and auditory injury, were based on cumulative SELs. In the static scenario for the oil tanker, TTS thresholds were exceeded for harbour porpoise within 905 m in the Singapore Strait and 1040 m in the Skagerrak. Auditory injury thresholds were exceeded within 80 m and 90 m, respectively. For the diving vessel the predicted TTS range was 300 m, with auditory injury within 20 m.

In the moving vessel scenario, maximum SELs occurred at the closest point of approach (CPA) and were modelled as a function of distance and vessel speed. For oil tanker travelling at 15 kn, TTS thresholds for harbour porpoises were exceeded at CPA distances up to 500 m in the Singapore Strait and 1000 m in the Skagerrak.

Overall, the results demonstrate that ultrasonic antifouling systems may cause adverse auditory and behavioural impacts, particularly for very high-frequency cetaceans such as harbour porpoises.

Table II: Predicted ranges of hearing impacts of noise emitted from the ultrasonic transducers onboard the crude oil tanker and diving vessel assuming that the vessel is static

Hearing Group	Effect	Impact range		
		Oil Tanker Singapore Strait	Oil Tanker Skagerrak	Diving Vessel Singapore Strait
Low-frequency cetaceans	Behavioural response	230 m	410 m	65 m
	TTS	5 m	5 m	-
	Auditory injury	-	-	-
High-frequency cetaceans	Behavioural response	230 m	410 m	65 m
	TTS	20 m	20 m	5 m
	Auditory injury	-	-	-
Very high-frequency cetaceans	Behavioural response	3075 m	3210 m	1725 m
	TTS	905 m	1040 m	300 m
	Auditory injury	80 m	90 m	20 m

4. Discussion and Conclusions

This study provides a quantitative assessment of the environmental implications of underwater noise generated by ultrasonic antifouling systems. The behavioural and auditory impacts on cetaceans were found to vary based on animal hearing group, vessel type, location, and exposure scenario. The most significant behavioural and auditory impacts were observed for very high-frequency cetaceans, particularly the harbour porpoise. Given their heightened auditory sensitivity in the ultrasonic frequency range (20–40 kHz), they were predicted to experience behavioural responses at distances exceeding three kilometres from the oil tanker and hearing impairment at distances nearing one kilometre under static exposure scenarios. These effects were more pronounced in acoustically reflective environments like the Skagerrak.

The moving vessel scenario, although representing shorter exposure durations, still indicated significant potential for TTS in harbour porpoises at distances up to 1000 m, depending on vessel speed and CPA. These findings suggest that even transient noise exposure from passing vessels may contribute to cumulative auditory stress in cetaceans.

Differences in impact between the two vessels highlight the importance of source level and transducer configuration. The diving vessel, with a smaller number of transducers and lower output, presented substantially reduced impact zones, suggesting that scale and power of ultrasonic systems directly influence environmental risk.

While ultrasonic antifouling systems offer a non-chemical alternative to conventional antifouling coatings, they may shift environmental impacts from chemical pollution to acoustic disturbance. This topic requires further attention, especially in ecologically sensitive or protected areas.

Mitigation measures should be considered to minimise acoustic risks. These may include temporal or spatial restrictions on the use of ultrasonic systems in areas known to host vulnerable species, particularly during mating seasons. Additionally, route planning avoiding feeding or breeding areas for marine mammals could be considered.

Future studies should aim to validate these modelling results with long-term field observations of marine mammal behaviour in proximity to vessels equipped with ultrasonic antifouling systems.

In conclusion, while ultrasonic antifouling systems present promising benefits in reducing biofouling without chemical agents, they pose measurable risks to marine mammals, particularly very high-frequency cetaceans. This subject should be further investigated.

Acknowledgement

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How Far Are We from an Internationally Harmonised Regulatory Framework for Biofouling Management?

Irene Øvstebø Tvedten, Bellona Foundation, Oslo/Norway, irene.tvedten@bellona.no

Abstract

The environmental benefits of biofouling management, including In-Water Cleaning (IWC), are widely acknowledged by the International Maritime Organization (IMO) and in the academic literature. However, the adoption of IWC practices remains hampered by the absence of a globally harmonised regulatory framework. Over the past year, significant steps have been taken towards international alignment. The International Organization for Standardization (ISO) has introduced two new standards for IWC: ISO 20679, focused on testing IWC systems, published in early 2025; and ISO 6319, which provides guidance on the conduct and documentation of IWC, currently in its final stages of development. Concurrently, the IMO has published Guidance on In-Water Cleaning of Ships' Biofouling in 2025. At MEPC 83 the very same year, member states agreed to develop a legally binding framework for the control and management of ships' biofouling. While an internationally harmonized regulatory framework for biofouling management has yet to be realized, building upon the foundation established in recent years could bring such a framework swiftly to implementation.

1. Introduction

Currently, ships seeking to perform In-Water Cleaning (IWC) must navigate a fragmented landscape of local and national regulations - often inconsistent, contradictory, or entirely absent. This lack of regulatory coherence not only imposes administrative burdens on both regulators and operators, but also discourages the frequency of cleaning. Reduced cleaning frequency undermines environmental best practices; proactive IWC - performed regularly to maintain hull cleanliness at Biofouling Rating 1 (BFR1) - has been identified as a key strategy to prevent the spread of invasive aquatic species (IAS), *IMO (2023)*. Moreover, in the absence of clear standards, IWC operations risk being conducted in ways that are not environmentally sound, potentially resulting in the uncontrolled release of IAS and harmful chemicals into marine ecosystems.

An internationally harmonised regulatory framework would address these issues, enabling consistent and efficient approval processes across jurisdictions. The IMO, as the principal international regulatory body for shipping, is best placed to lead this harmonisation effort. Encouragingly, in April 2025, the IMO agreed to develop a global, legally binding instrument for biofouling management. However, given the complexity and procedural demands of international treaty-making, such a framework will likely take a decade or more to finalize and ratify.

In the interim, local and national regulators are shaping global IWC practices, and their policies and experiences should inform the IMO's regulatory development process. More importantly, in the absence of binding international rules, national authorities should strive for alignment with existing international guidance - specifically, the IMO 2023 Biofouling Guidelines and the IMO 2025 Guidance on In-Water Cleaning of Ships' Biofouling. Additionally, two new ISO standards - ISO 20679 and the forthcoming ISO 6319 - offer technical frameworks that can support streamlined approval processes and ensure that IWC is conducted in a manner that safeguards marine environments.

2. ISO

The recent development of two ISO standards represents a significant step forward in supporting internationally harmonised biofouling management practices. Both applies broadly across IWC scenarios - all levels of fouling, all submerged external surfaces, and operations with or without debris capture. ISO 20679 establishes detailed procedures for the independent performance testing of all forms of IWC. It defines testing protocols, specifies how to generate and report data, and outlines methods for evaluating the efficacy and environmental safety of IWC systems. ISO 6319, currently in its final stages of approval, sets out requirements and best practices for the safe, efficient, and environmentally responsible planning and execution of IWC operations. The standard aims to support decision-making by port authorities and regulators when assessing requests for IWC in port or at anchorage.

Both ISO 20679 and ISO 6319 do not establish performance thresholds or regulatory criteria for IWC systems. The responsibility for setting such criteria lies with individual authorities, agencies, or administrations. However, these ISO standards can support regulators by providing structured methodologies and reliable data to inform the development of performance requirements. Both ISO standards are aligned with existing IMO guidelines and guidance on biofouling management, ensuring coherence across technical and regulatory frameworks.

3. IMO

At its 83rd session in April 2025, the Marine Environment Protection Committee (MEPC) of the IMO agreed to begin the development of a legally binding framework for the control and management of ships' biofouling, with the goal of minimizing the transfer of invasive aquatic species (IAS). This marks a turning point in global maritime environmental policy. However, it remains to see what performance criteria the IMO is going to set.

Currently, a variety of national and regional regulatory approaches are emerging, offering potential models for the future global framework. For example, New Zealand requires ships to arrive with a "clean hull," which refers to a slime layer on the hull, and mandates that IWC be recently conducted prior to arrival. If the forthcoming IMO framework adopts a similarly stringent standard—such as requiring hulls to be maintained at Biofouling Resistance Level 1 (BFR1)—frequent and accessible IWC will be essential.

In this context, ISO 20679 and ISO 6319 may prove helpful. These standards can support the efficient approval of cleaning operations and ensure that they meet defined environmental and technical benchmarks. If the new IMO framework introduces specific performance criteria for IWC—whether for capture efficiency, cleaning efficacy, or risk management—ISO standards can offer a basis for consistent documentation and verification by shipowners, service providers, and port authorities alike. This will help ensure environmentally sound IWC processes.

4. Conclusion

In conclusion, while the development of a binding international regulatory framework is still in its early stages, tools such as ISO 20679, ISO 6319, and the IMO's own guidance documents provide the technical scaffolding needed to support harmonisation in the interim—and to shape a robust, science-based global approach in the years ahead. In developing a future regulatory framework for biofouling management, the IMO need not begin anew; rather, it would be prudent to build upon the substantial foundation already laid through existing guidelines, guidance documents, and relevant ISO standards. Anchoring the process in this established consensus not only enhances efficiency but also ensures continuity and acknowledges the considerable work already undertaken in this domain.

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Shipping Companies' Expectations Regarding Proactive Cleaning: The CMA CGM Case

Jean-Loup Barrère, CMA CGM, Marseille/France, ext.jbarrere@cmaships.com

Abstract

The text discusses the shift from reactive to proactive cleaning systems for ship hulls using soft brushes and autonomous drones. Proactive cleaning requires cleaning every few weeks, which poses challenges for shipping companies with hundreds of ships calling at various ports. A 100% autonomous on-board cleaning system is needed, which raises concerns about positioning, communication, and home docking. Additionally, port authorities may require prior authorization for proactive cleaning, making a system operational during transits preferable. A few startups have taken on this challenge, which includes addressing hydrodynamics and energy autonomy.

1. Introduction

The fight against biofouling dates back to antiquity, when the Phoenicians and Romans used natural materials like tar to protect ship hulls. In the 17th century, copper plates emerged, providing effective protection against fouling, although galvanic corrosion was an issue. In the 19th century, copper- and arsenic-based antifouling paints were developed, followed in the 1960s by TBT (Tributyltin) paints, which were highly effective but extremely toxic to marine ecosystems.

In response to these environmental impacts, TBT was banned in 2008 by the IMO, paving the way for more sustainable solutions like foul-release coatings, which prevent organism adhesion without biocides. Today, hull cleaning can be carried out by divers or by underwater drones. But this strategy of reactive cleaning does not give the best possible results.

It is now possible, thanks to innovative technologies such as autonomous cleaning robots, to enable proactive hull maintenance which looks like the best possible solution. While a few systems are already commercialized, others are still under development. This paper explores the expectations of shipping companies and the technical barriers that must be overcome to meet these expectations.

2. Current situation about the biofouling

2.1. The biofouling issue

Biofouling refers to the accumulation of marine organisms, such as algae, barnacles, and mussels, on ship hulls. This growth increases surface roughness, causing drag and reducing the hydrodynamic efficiency of vessels. As a result, ships require more energy to maintain speed, leading to higher fuel consumption and operational costs.

Biofouling can increase a ship's fuel consumption by up to 20-40%, depending on the severity, https://www.glofouling.imo.org/_files/ugd/34a7be_02bd986766d44728b85228c3ec9b95ee.pdf. This overconsumption leads to higher emissions of greenhouse gases (GHGs), contributing significantly to global warming. The International Maritime Organization (IMO) estimates that shipping accounts for nearly 3% of global CO_2 emissions, a figure exacerbated by biofouling.

2.2. Existing Solutions for Hull Inspection and Cleaning

For hull inspections, the options are:

- Divers: Traditionally, divers inspect hulls for biofouling but face limitations in accuracy and safety. This makes it difficult to get a good appreciation of the hull condition.

- Remotely Operated Vehicles (ROVs): ROVs are increasingly used for detailed hull inspections, offering greater precision and safety.

For cleaning, the options are:

- Antifouling Coatings: Specialized paints with biocides or foul-release properties that deter organism attachment.
- Reactive Cleaning: Performed after biofouling has accumulated and been detected thanks to hull inspection; involves abrasive cleaning systems (mainly divers with brushes) or high-pressure water jets (mainly with ROVs).
- Proactive Cleaning: Regular cleaning with soft brushes to prevent significant biofouling buildup. Emerging technology.

2.3. Main Regulations on Biofouling Management

IMO Biofouling Guidelines (2011):

- Provides recommendations for minimizing biofouling to reduce GHG emissions and prevent the transfer of invasive aquatic species.
- Encourages the adoption of biofouling management plans and record books.

Australian and New Zealand Biofouling Requirements:

- Mandate biofouling management documentation for vessels entering their waters to prevent the introduction of invasive species.

US Environmental Protection Agency (EPA):

- Includes biofouling management in the Vessel General Permit (VGP), requiring vessels to minimize hull fouling and use approved antifouling coatings.

EU Regulations:

- While there is no unified EU regulation, individual countries like the Netherlands and Norway have strict controls on biofouling management and cleaning in their waters.

3. Why should we go for proactive cleaning?

Proactive hull cleaning, also often referred to as "hull grooming," is considered the best solution for maintaining clean hulls and fighting against biofouling due to several significant advantages over reactive cleaning methods.

Here's why:

- <u>Prevent biofouling from taking hold</u>: Proactive cleaning focuses on removing early-stage biofouling, such as microscopic slime and biofilms, before it can develop into larger, more firmly attached macrofouling (like barnacles and mussels). This prevents the entire biofouling process from progressing to a problematic stage.
- <u>Maintains optimal hull performance</u>: Even a light layer of slime can significantly increase fuel consumption. By consistently removing this early-stage fouling, proactive cleaning ensures the hull remains smooth and minimizes drag, thereby optimizing fuel efficiency and reducing operational costs. An IMO report, https://www.glofouling.imo.org/_files/ugd/34a7be_02bd986766d44728b85228c3ec9b95ee.pdf, shows even a light slime layer can increase fuel consumption by up to 25%, while heavy fouling can lead to increases of over 50%, Fig.1.
- <u>Reduce emissions</u>: Directly linked to fuel efficiency, a cleaner hull translates to lower fuel consumption, Fig.2, and, consequently, reduced emissions of greenhouse gases (like CO_2) and other pollutants (like SOx and NOx). This is crucial for complying with increasingly stringent environmental regulations and for a more sustainable shipping industry.

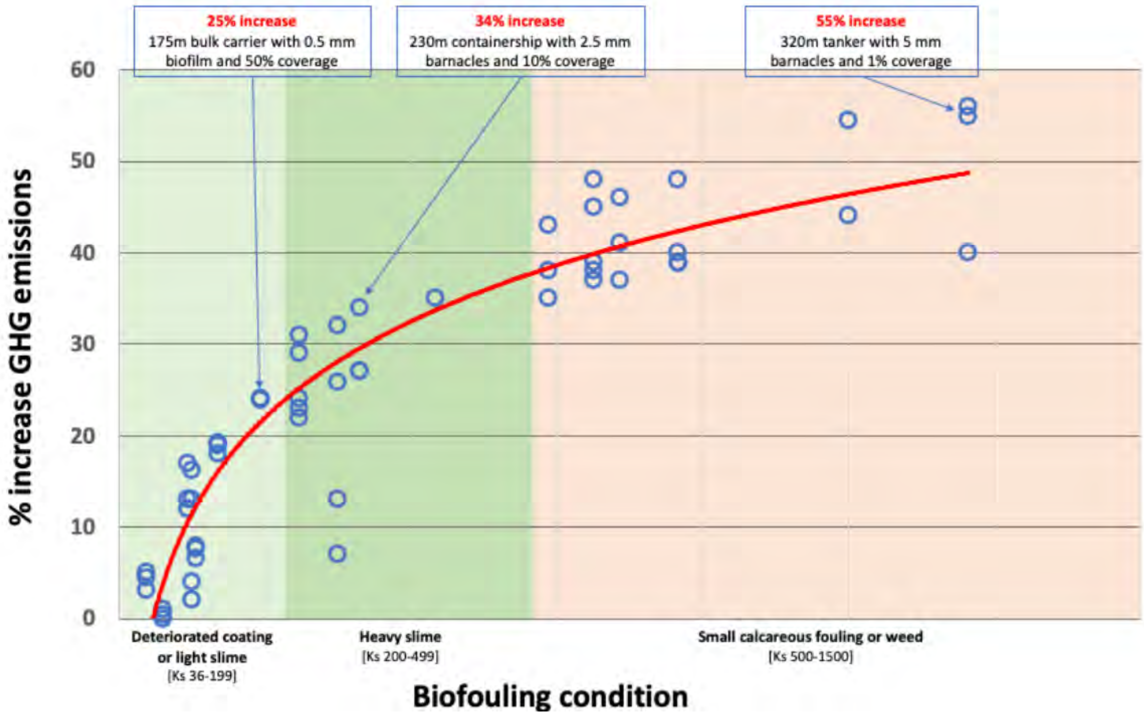

Fig.1: GHG emission/ fuel over consumption versus biofouling condition

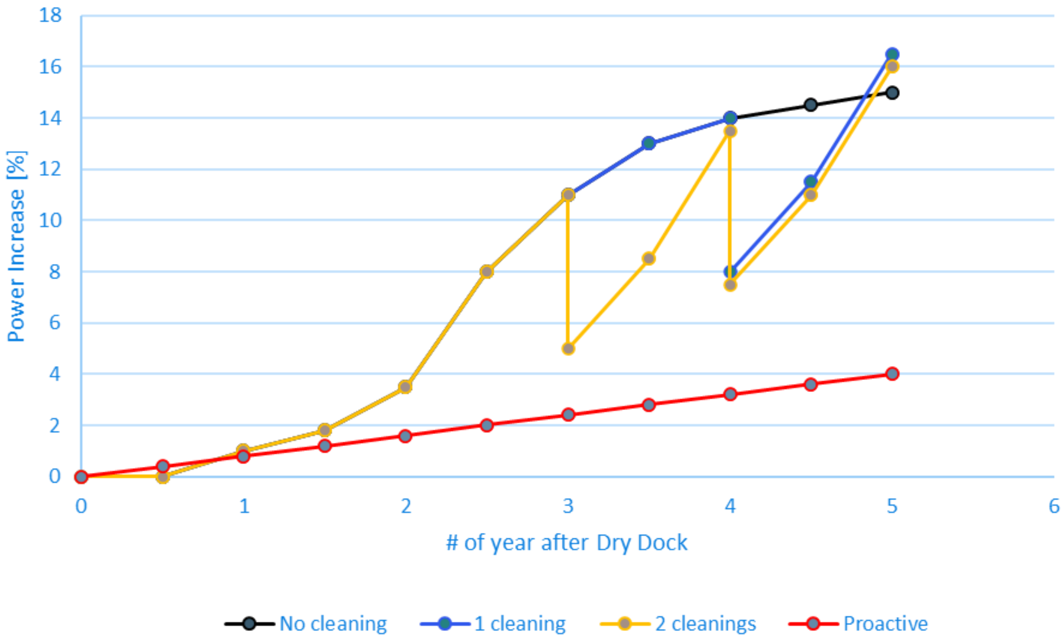

Fig.2: Power increase – Reactive versus proactive

- <u>Protect anti-fouling coatings</u>: Reactive cleaning, which deals with heavy fouling, often requires more aggressive cleaning methods that can damage the vessel's anti-fouling coatings. This shortens the lifespan of the coating, requiring more frequent reapplication and increasing overall maintenance costs. Proactive cleaning, being gentler and more frequent, helps preserve the integrity and effectiveness of the anti-fouling paint for longer.
- <u>Minimize the spread of invasive species</u>: Biofouling is a major pathway for the transfer of invasive aquatic species to non-native environments. By preventing significant biofouling accumulation, proactive cleaning drastically reduces the risk of transporting these species, which can have devastating ecological and economic impacts on local ecosystems.

- Reduce costs in the long run: Less fuel consumption, extended coating life, and avoiding expensive reactive cleaning (which might even require dry-docking or specialized capture systems for removed debris) contribute to a lower overall operating expenditure.
- Avoid using anti-fouling coatings: A frequent proactive cleaning system (e.g. every 1 or 2 weeks) may even allow standard hard coating without any biocides which means that no toxic products would be released in the environment by the coating any longer.

In essence, proactive cleaning shifts the paradigm from a "cure the problem" approach to a "prevent the problem" approach, offering a more efficient, cost-effective, and environmentally responsible solution to the challenges of marine biofouling.

4. Main proactive cleaning requirements

For ships with short rotation duration, it may be possible to use systems operated from the dock or installed on board, with a tether, and which could be locally (or remotely) operated. But these systems face several weaknesses:

- When the ship is docked, the fences on the dock side prevent the use of a drone with a tether, which means that only the seaside and the flat bottom can be cleaned.
- The ports overload makes the schedule of ships change all the time which makes the cleaning operation difficult to organize.
- Using a tether, even with an automatic system means that an operator must be available 24h/24h in case the tether would get entangled.
- Using a ROV in a port means that the ROV shall be authorized by the port authorities which is a long and difficult process. This means that only the main large ports may be possible for this kind of system at first.
- Any ship which started with a proactive cleaning policy must be cleaned often enough to prevent the fouling to become too thick and resistant to be cleaned by a proactive cleaning ROV. This means that the rotation duration must be regular and short enough, and also that the ship must not change line where proactive cleaning would not be possible.

The requirements below are mostly linked to the operations of long-haul ships. They are based on the following operational constraints:

- Avoiding fouling to become more than slight slime means that proactive hull cleaning must be done on a regular basis with intervals which may depend on sea temperature and ship idle times but cannot exceed a few weeks.

  Considering that:

  - In most ports and despite IMO recommendations, the cleaning system needs to be approved, which is a long and costly process,
  - Large shipping companies have hundreds of vessels calling into hundreds of ports,
  - The mean rotation duration of long-haul ships is often too long (average ≈ 60 days for CMA CGM) to use only one port per line for proactive cleaning.

  Thus, having a proactive system operated from the dock would mean having approval from all ports at once which is not reasonable. This means that the system must be installed on board and that the cleaning must be done during transits.

- Having the system on board implies that the system must not add any workload to the crew. So, the system must be fully automatic.

Id	Requirement	Description
1	CLEANING SYSTEM	
1.1	Operations	The proactive cleaning system shall operate while the ship is sailing
1.2	Operations	The proactive cleaning system shall operate in full autonomy once the cleaning started
1.3	Cleaning start	The proactive cleaning system shall be started by various events such as: • A local decision from the board who can decide to start a cleaning without warning anyone. • A remote order from a supervision system somewhere on land or on board
1.4	Tether	Using a tether is not allowed for crawlers: in case of entanglement, as there is no local operator, it may be impossible to solve the entanglement issue remotely. Using a tether is possible but only for ROV which are able to fly underwater. In that case, there is still a risk of entanglement which means that it is required that a remote operator must be available 24/24 for solving the entanglement issue.
1.5	Operations	There shall be no preventive operation on board prior to a hull cleaning to stop any ongoing operations (pumps, machines…), which could damage the drone or prevent the cleaning operations. It is up to the drone to avoid the dangerous areas. These areas shall be identified automatically by the drone or entered in the drone parameters during the system installation.
1.6	Installation	There shall be no hull marking/tagging to demarcate forbidden areas or help the drone for positioning
1.7	Cleaning	The cleaning operations for the 2 verticals shall not last more than 24 hours (for in-port cleaning drones) or 36 hours (for in-transit cleaning drones)
1.8	Cleaning	The cleaning operations for the 2 verticals and the flat bottom shall not last more than 36 hours (for in-port cleaning drones) or 96 hours (for in-transit cleaning drones)
1.9	Cleaning	The drone shall be able to go to the flat bottom for inspection and cleaning and handle the bilge keels positions
1.10	Cleaning	The drone shall be able to clean a specific zone in order to clean the hull in several times
1.11	Inspection	The cleaning system shall be able to carry out on request the inspection of a specified zone
1.12	Communication	If there is no tether, there shall be a way to send a message to the drone to order its return to the docking station (“End of mission”): this is especially important in case the ship must leave while there is a cleaning operation ongoing.
1.13	Communication	After an “End of mission” order, the system shall be in standby mode within 30 minutes (drone back to the docking station and stored)
2	MAIN DRONE FUNCTIONS	
2.1	Positioning	The drone shall include a high precision positioning system which precision shall be better than HxL = 10x50 cm on the hull after 1 hour of cleaning and less than 10x100 cm at all times.
2.2	Positioning	Autonomous drone: The drone shall be able to go back to its docking station and plug itself automatically to recharge its batteries if needed
2.3	Positioning	Tethered drone: The drone shall be able to go back to its docking station

Id	Requirement	Description
2.4	Tether	Tethered drone: The drone must be able to pull the umbilical cable in all directions to free itself in the event of the umbilical getting caught. This means that the drone must be able to fly away from the hull and have at least 5 degrees of freedom for pulling in the right direction.
2.5	Cleaning	The drone shall be able to maintain a constant cleaning intensity and to adapt the cleaning intensity to the fouling level
2.6	Security	Crawlers: for crawlers using a magnetic attachment, there is a risk of detachment which could result in the loss of the drone. To mitigate this risk, the crawler shall include 2 functions: - Forbidden area avoidance - Emergency recovery system
2.6.1	Security	Forbidden area avoidance for crawlers: the crawler must avoid dangerous areas where it could detach from the hull such as water exhaust pipes, grids, curved areas….
2.7	Security	The drone shall be able to detect and automatically avoid any unexpected obstacle such as a fender or a drug chest.
2.8	Security	Tethered drone: the drone must be able to detect any entanglement and automatically send an alarm to the supervision system via the docking station for a remote operator to intervene in an emergency.
2.9	Reliability	For autonomous crawlers, a risk analysis shall be done to demonstrate that the failure rate for the loss of a drone is lower than $\lambda = 1/MTTF = 10^{-5}$ / h (This means less than 1 drone lost per year when used 48 h/month on 100 ships). Drone losses will be at the supplier's costs: it is up to the supplier to evaluate the risks and find the best economical solution.
2.10	Battery	For autonomous crawlers, the drone shall monitor the battery level and prevent the battery level from becoming too low by starting a recharge procedure before. The battery monitoring shall also evaluate the battery capacity which may decrease when the battery ages.
2.11	Battery	Tethered drones shall be powered by the docking station
2.12	Video	The drone shall take a video of the hull or at least enough pictures for creating a full hull mapping in FHD resolution. There shall be records before and after the cleaning in order to evaluate the hull state before cleaning as well as the cleaning efficiency. For autonomous crawlers, both video streams shall be recorded locally in the drone and uploaded to the docking station afterwards.
2.13	Communication	The drone shall include a communication system with the docking station for sending its status and receiving "End of Mission" orders.
2.14	Operations	The drone shall come back to the docking station in case of: - The cleaning pattern which was programmed is complete. - The battery is too low and shall be recharged by the docking station. - "End of mission" message received from the docking station. - Any failure detection (except if the failure does not allow it).
2.15	Maintenance	The drone shall be able to carry out a full autotest and to send the results to the supervision software through the docking station
2.16	Communication	When connected to the docking station, the drone shall communicate to: - send its internal status. - send the videos/pictures which are being taken or has been recorded. - receive a cleaning configuration pattern and forbidden areas. - receive a start cleaning order

3	DOCKING STATION	
3.1	Size	The docking station shall not be larger than 1m wide x 4 m long
3.2	Interfaces	The docking station shall be connected to the onboard network (for communicating with the status console on the deck) : this implies that the docking station shall meet the cyber security requirements of the shipping company
3.3	Interfaces	The docking station shall be connected to the onboard freshwater supply.
3.4	Power	The docking station shall support two possible power supplies: 440 V x 60 Hz or 220V x 50 Hz. Its power consumption shall be lower than 3 kW
3.5	Operations	The drone shall stay in the docking station when it is not in operation
3.6	Tether	For tethered drones, there shall be a reel with an automatic tension system for keeping the tether length in the water as short as possible
3.7	Operations	For swimming drones, the drone shall be pulled out of the water from the docking station and stored properly in the docking station
3.8	Operations	The drone shall be able to go from the docking station to the area where the cleaning shall start without any human intervention
3.9	Processing	The drone or the docking station shall include post-processing for extracting significant pictures with their positions instead of sending raw videos: 12 hours of FHD video represents at least 10 Gbytes of data, it does not seem reasonable to rely on the local GSM network for sending such amounts of data nor any satellite communication link. There shall be at least 3 FHD pictures for each area measuring 15 m long x 2 m high.
3.10	Processing	The FHD pictures shall also be sent to the CMA CGM Cloud Inspection software using the API provided by CMA CGM
3.11	Battery	Autonomous drones: the charging procedure shall be short enough for meeting the requirement about a full hull cleaning duration
3.12	Maintenance	The docking station shall be able to fully rinse the drone with fresh water for preventing salt accumulation and corrosion
3.13	Maintenance	The docking station shall take video/pictures of the drone to allow a remote operator to evaluate its external state
3.14	Security	The docking station shall be secured to prevent any parts to be stolen (which is a risk because of stevedores coming on board during calls)
4	ENVIRONNEMENT	
4.1	Current	Tethered drones: Cleaning shall be possible with a current of up to 2 kts
4.2	Temperature	The system can be used in the following conditions: Water T°C: 0°C to +30°C – Air T°C: +1°C to +50°C
4.3	Temperature	The system shall measure the air temperature and shall prevent the system from starting a cleaning when the air temperature is below 0°C (to prevent any malfunction due to ice in the docking station or on the drone)
4.4	Temperature	There shall be no rinsing in the docking station when the air temperature is below 0°C
4.5	Temperature	The system can be used in the following conditions: Water T°C: 0°C to +30°C – Air T°C: 1°C to +45°C
4.6	Temperature	The system can withstand the following conditions in standby mode: Air T°C: -30°C to +60°C

5	COMMERCIAL	
5.1	Installation	The installation can be done within 48 hours during a call. This includes: - Removing the guardrail - Installing the docking station - Installing the control/status device on the deck - Configuring the drone and the docking station
5.2	Business Model	Business Model shall be either: • Robot as a Service (RaaS) • System sold to customer + Maintenance contract

5. Technical barriers

Designing a system meeting the requirements listed above means that several technical barriers must be solved:

- Grip and hydrodynamics
  When moving underwater on the hull, the drone must stay on the hull without sliding in real navigation conditions. This means that the drone shall have a profile such as the drift force due to the water flow will not push or pull the drone too much: an inappropriate shape may lead to forces up to 2 tons for a 1 m^2 drone at 20 kn… The drag force due to the water flow must not exceed the limit causing the drone to slide on the hull.

- Positioning on the hull and obstacle detection
  Positioning the drone precisely on the hull by using cheap sensors is quite challenging but possible with techniques such as video processing, odometry, and AHRS/IMU sensors (Inertial Measurement Unit). Other sensors may be used (e.g. DVL, Sonar…) but they will increase the cost of the ROV significantly. Detecting obstacles such as grids, mussels, drug chests… which may prevent the drone from moving forward or create a risk of detachment from the hull, may be difficult to design at low cost.

- Energy autonomy
  Moving on a hull while the ship is sailing and cleaning the hull at the same time may be quite power consuming: the drone shall spend as little as energy as possible to clean and fight again the drag force. The autonomous drone must then be able to save as much energy as possible and be able to recharge its batteries quickly and easily.

- Communication with the docking station
  The drone must communicate securely with the docking station while underwater and in transit. Radio link is not possible underwater with usual radio frequencies. So, this point is pretty difficult to solve except by having the drone going out of the water from time to time and establish a standard radio link with the docking station. But going out of the water means going through the splash zone which is the most dangerous place for the drone.

- Robustness and safety
  The drone must stay in a very harsh environment with low and high temperatures, marine corrosion, watertightness requirements ...etc. The robustness shall be part of the initial design to prevent any failure from causing the loss of the drone. This means high quality hardware and software, hardware redundancy, safety sensors and systems…

- Return to the docking station
  Returning to the docking station means having a high precision positioning system close to the docking station, a solution for going into the station in the right way and a reliable solution to charge and communicate with the drone.

6. Expected benefits and ROI for shipping companies

As the power increase curve is symmetric, it means that the average power increase is around half of the maximum value before dry dock minus the savings due to the reactive hull cleanings.

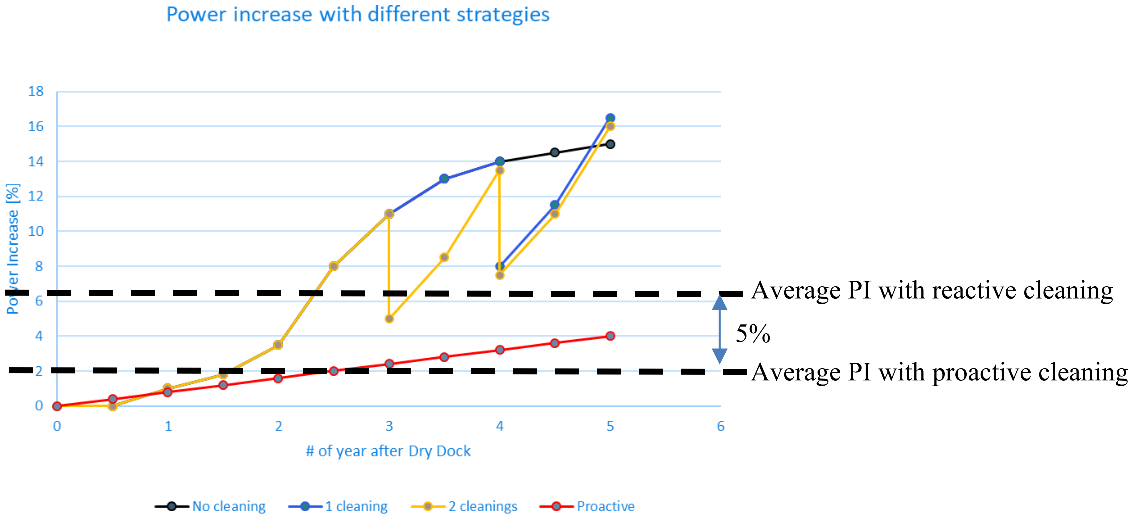

Fig.1 : Estimation of fuel savings

The actual fuel savings can then be processed by subtracting the average power increase (PI) with reactive cleaning from the average PI with proactive cleaning. According to our investigations, there is no reliable figure yet on the actual PI with proactive cleaning on large ships: the red curve is an estimation about our expectations considering that the proactive cleaning may not be perfect and the hull roughness may increase a little bit during the 5 years between dry docks.

In our example, this leads to an average fuel saving of 5% along the ship life between 2 drydocks.

Let's now take as an example 3 types of container ships, considering 5% of fuel savings:

LOA	**200 m**	**300 m**	**400 m**
Average fuel per year	8 745 t	24 635 t	32 980 t
Main engine power consumption in good weather conditions [80%(Main Engine) x 85%(Weather)]	5 946 t	16 752 t	22 427 t
Savings due to proactive cleaning without carbon costs	$ 225 000	$ 587 000	$ 1 153 000
Savings due to proactive cleaning with carbon costs	$ 310 000	$ 846 000	$ 1 435 000
Proactive cleaning costs with RaaS model (/ year/ship)	$ 30 000 $ 60 000 **$ 100 000**	$ 30 000 $ 60 000 $ 100 000	$ 30 000 $ 60 000 $ 100 000
Return On Investment (without carbon costs)	55 days 130 days **283 days**	19 days 41 days 74 days	10 days 20 days 34 days
Return On Investment (considering carbon costs)	39 days 86 days **171 days**	13 days 28 days 49 days	8 days 16 days 27 days

The "Average fuel per year" was processed with 5 to 10 ships of each sizes cruising on various lines. The "Main engine power consumption in good weather conditions" considers that 20% of the fuel consumption is due to auxiliary engines and 80% for the main engine, and that 15% of the fuel consumption of the main engine is due to bad weather conditions.

Note that some of the 400 m ships use LNG; this was taken into account in the carbon costs.

Fuel savings are not the only savings: saving fuel means saving GHG emissions which has also a cost.

Several annual fees were considered (30k$, 60k$, 100k$). The table shows that for 200 m ships, an annual fee of 100 k$ is barely acceptable (ROI is 6 months with carbon costs and 9 months without carbon costs which means almost no benefits): this looks like the upper limit for the annual fee for renting a proactive cleaning system which includes:

- 2 ROV's (1 one for each side)
- 2 docking stations (1 one for each side)
- 1 status console on the deck

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Ultrasonic In-Water Cleaning and Microplastic Release

Matthias Bork, CoaST, Technical University of Denmark, Lyngby/Denmark, merbo@kt.dtu.dk
Pascal Guth, CoaST, Technical University of Denmark, Lyngby/Denmark, pagut@kt.dtu.dk
Huichao Bi, CoaST, Technical University of Denmark, Lyngby/Denmark, hubi@kt.dtu.dk
Søren Kiil, CoaST, Technical University of Denmark, Lyngby/Denmark, SK@kt.dtu.dk
Kim Dam-Johansen, CoaST, Technical University of Denmark, Lyngby/Denmark, KDJ@kt.dtu.dk

Abstract

Ultrasonic in-water cleaning was performed in a laboratory scale setup on an antifouling yacht coating under controlled conditions. Under harsher cleaning conditions, the entire leached layer could be removed resulting in visible damage. As the coating was exposed to these conditions for longer, the extent of damage increased. The removed leached layer was released as microplastic particles (<100 µm) to the seawater. Under less harsh conditions, no visible damage to the coating was observed, regardless of exposure time. However, microplastic release could also be measured under these conditions.

1. Introduction

In-water cleaning is a vital procedure for maintaining coating performance and biofouling-free ship hulls. Different cleaning technologies and strategies can be effective for removing fouling. Brush cleaning where (rotating) cleaning brushes are used to directly remove fouling is the most common technology due to its simplicity and cost-effectiveness, *Hearin et al. (2016)*. Another technology is ultrasonic cleaning, where probes vibrate at ultrasonic frequencies to produce and subsequently implode tiny bubbles in the water. This energy from the implosions results in the removal of fouling from the surface. This is a contactless method, which was developed to reduce damage to antifouling coatings, *Morrisey and Wood (2015)*.

When an antifouling coating is exposed to seawater, the biocides at the coating surface dissolve and a porous leached layer is formed. This leached layer is essential for controlling the release of biocides and extending the lifetime of the coating. However, the leached layers of self-polishing coatings are also structurally weaker than the bulk of the coating, *Bressy et al. (2009)*.

Coating damage during cleaning should be minimised to preserve a coatings lifetime and effectiveness, and reduce biocide release, *Oliveira and Granhag (2020)*. Nevertheless, visible damage is common after cleaning. This damage has also been stated as a cause of increased antifouling paint particle (APP) concentrations in marinas and shipyards, *Turner (2010)*. APPs are a type of microplastic originating from antifouling coatings, characterized by their high metal content from biocides in the coating. In addition to the issues general microplastics can cause, these particles leach out biocides possibly resulting in harm to non-target organisms. However, the extent to which in-water cleaning contributes to the release of APPs is unclear, as other release pathways have also been identified, *Tamburri et al. (2022)*.

The release of particulate matter from cleaning has been investigated by *Soon et al. (2021)* by analysing the cleaning effluents from manual in-water cleaning of a ship. They found high concentration of suspended solids and high metal concentrations, attributed to the antifouling coating on the ship. The majority of the particulate matter found had a particle size of above 8 µm. However, this method was not selective for paint particles and therefore also included fouling species in the measurement. In this work, microplastic release during ultrasonic in-water cleaning was investigated under controlled conditions. This way, there is no interference from biofouling and all released matter can be inferred to originate from the coating.

2. Exposure and cleaning

A self-polishing antifouling yacht coating (100-150 µm dry film thickness) was applied to primed PVC panels and exposed under controlled conditions (20 °C, 20 knots, 3.5 % salinity) before a cleaning procedure was applied. Cleaning of antifouling coatings is not performed on fresh coatings, as significant fouling typically only develops after a ship has been in the water for several weeks. Therefore, exposure is essential for simulating realistic conditions for investigating the impact of cleaning. As such, the coating was exposed for 50 days on a rotary drum, *Kiil (2001)*. After this time, a leached layer had developed and controlled cleaning was performed.

A square of the coating was cut out and placed in a holder such that a 30x30 mm area of the coating was exposed. The coating in the holder was submerged in filtered artificial seawater and an ultrasonic probe (14 mm diameter) was secured at a height of 10 or 40 mm above the center of the sample, Fig.1. The probe was activated at a frequency of 26 kHz and an amplitude of 90 µm for 5, 15 or 25 s. The probe heights and cleaning times used were based on experiments on fouled panels with the same coating which showed these settings were appropriate for removing fouling.

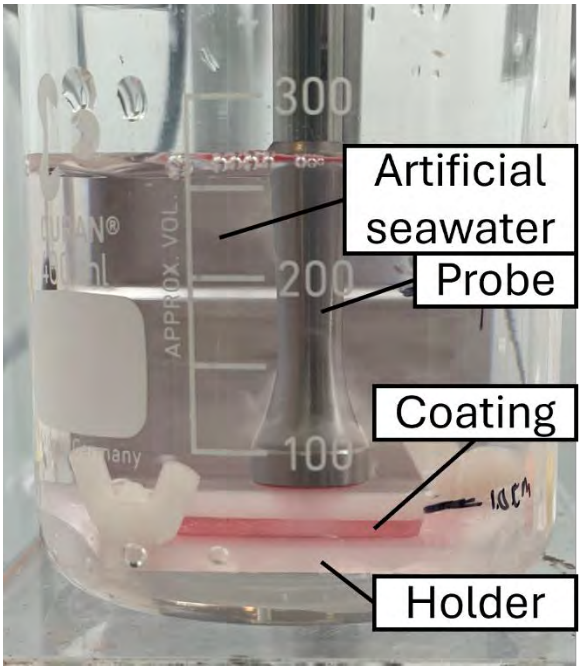


Fig.1: Ultrasonic cleaning setup

3. Coating damage inspection

Fig.2 shows images of the coating samples after ultrasonic cleaning. The horizontal scratches are from the dynamic exposure as they were present on the coating before cleaning. Damage from the cleaning is clearly visible at the center of the samples where cleaning was performed at a probe height of 10 mm. The size of the spot of damage increases with increasing cleaning time. The sizes of the spots were recorded through image analysis of the samples.

Fig.3 shows a cross-section of the area with visible spots of damage. This cross-section was taken at the edge of the damage spot of the t:25 s h:10 mm sample. On the left side, a leached layer of around 20 µm is visible. On the right side, the side of the damage spot, nearly the entire 20 µm leached layer is absent. Similar cross-sections were made for all samples, and the leached layer thicknesses were recorded. The total volume removed during cleaning can be calculated by multiplying the leached layer thickness and the area of the visible spot. This total volume will be used to compare to the total volume of released particles.

While the damage to the samples with 10 mm probe height samples is clear, no visible damage is observed for the 40 mm probe height samples, even after 25 s. The difference in probe height results in a difference in area affected by the ultrasonic probe, as the waves propagate from the probe and spread out, the energy density decreases. As such, the energy per area affecting the coating is lower at 40 mm probe height compared to 10 mm. Apparently, a threshold has been crossed where the energy density is not sufficient to remove the leached layer.

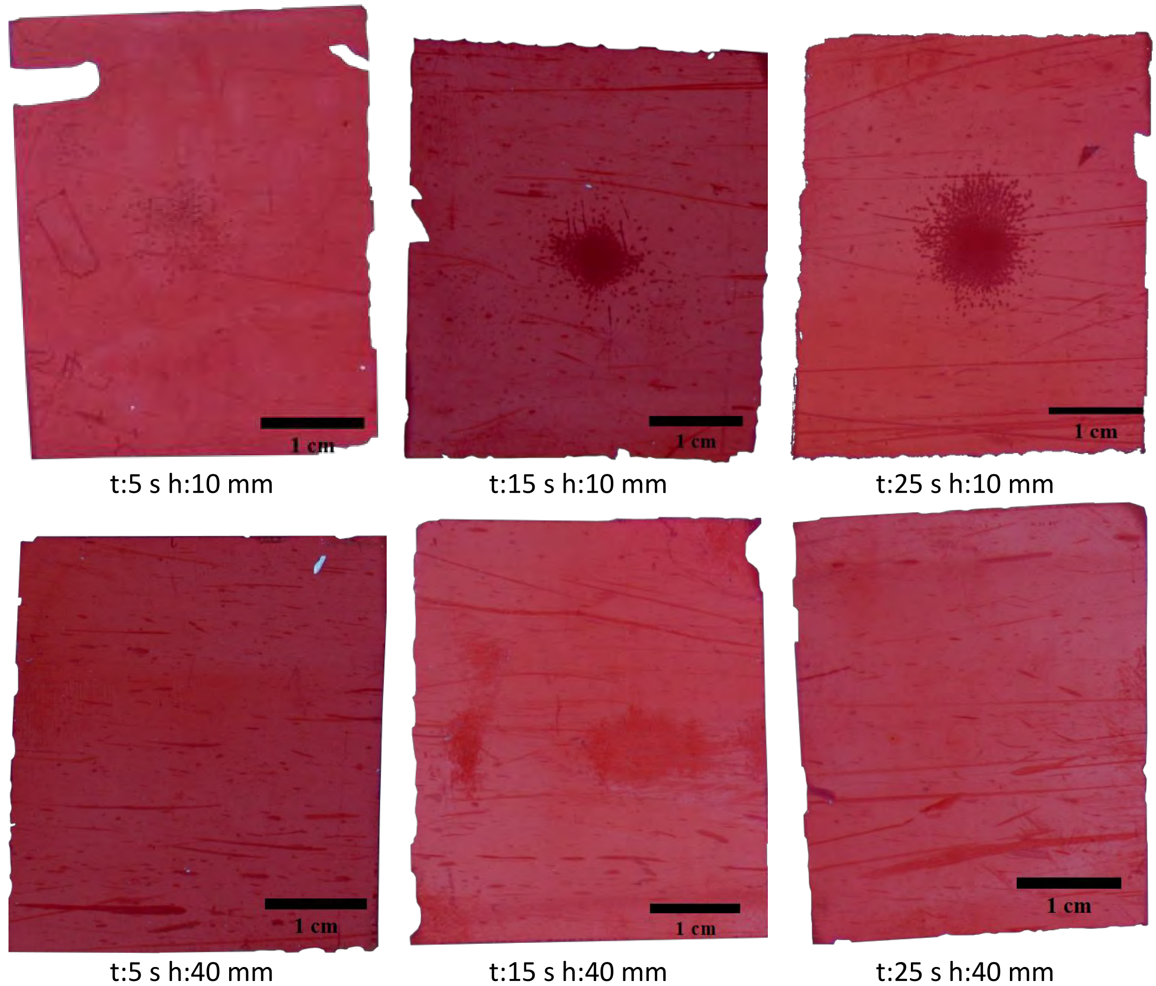


Fig.2: Pictures of the coating samples after ultrasonic cleaning at different cleaning times (t) and probe heights (h)

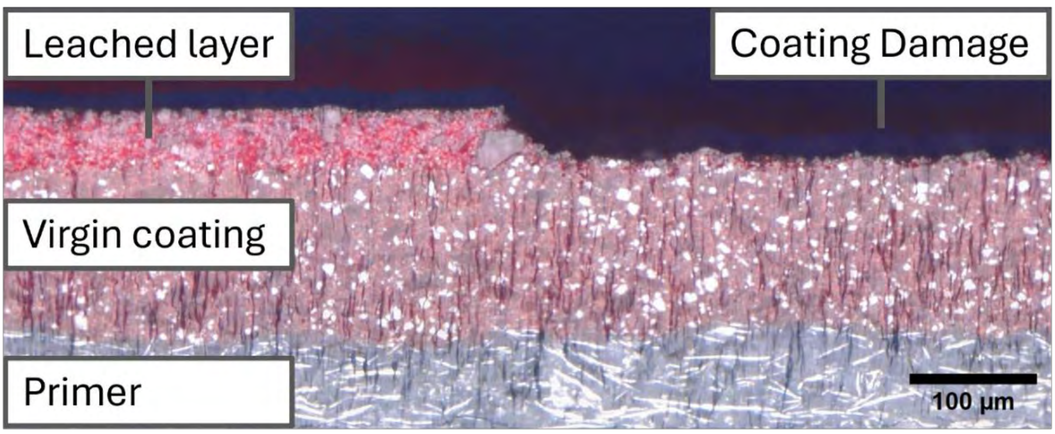
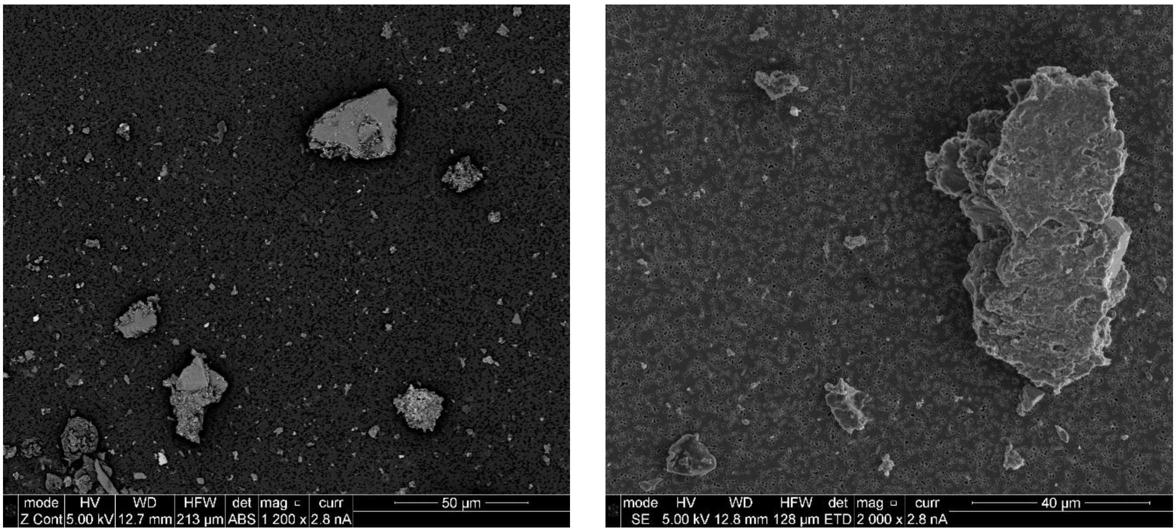


Fig.3: Light microscope image of a cross-section of sample t:25s h:10mm. The spot damage can be seen on the right (labelled “Coating Damage”) and the intact leached layer on the left.

4. Microplastic release

After each cleaning was performed, a 5 mL liquid sample of the artificial seawater in the beaker was taken and filtered over a track-etched polycarbonate filter with a pore size of 0.4 µm. Using scanning electron microscopy (ThermoFisher HELIOS Nanolab, ETD&ABS detectors, 5 kV, 2.8 nA, high vacuum) the particles on the filters were imaged at high magnifications. Fig.4 shows two images of some of these particles. Fig.4a highlights the variety of particle sizes recovered. Most particles are around 1-5 µm; however, larger particles were also found. The structure of the larger particles resembles the microstructure of the leached layer, and they contain large fillers and smaller biocides. This is especially clear in Fig.4b, which shows an exceptionally large fragment of about 40x80 µm. Increasing numeric abundance as particle size decreases and the presence of biocides has also been observed in APPs found in the environment, *Song et al. (2014), Soroldoni et al. (2018)*.



(a) (b)

Fig.4: Scanning electron microscope images of particles released during cleaning

The particles were also analyzed using an automated scanning electron microscopy (SEM) procedure, which records particle numbers and morphological data, among other data. This methodology was adapted from *Bork et al. (2025).* By extrapolation of recorded particle volumes, total particle volumes were obtained. Fig.5 shows a comparison of the extrapolated particle volumes, and the volumes calculated from the image and cross-sectional analysis.

Note that there are no calculated volume values for the 40 mm probe height samples, this is due to the lack of visible damage from cleaning for these samples. Nevertheless, measurable total particle volumes were still found, albeit much less than the 10 mm probe height samples. This indicates that, while these cleaning parameters caused no visible damage to the coating surface, some particles were still released. Likely, only the very top layer of the leached layer was removed. If it is assumed that the ultrasonic waves affect the entire surface equally, the total particle volumes here equate to a layer with a thickness of 0.16-0.40 µm. The removal of such a thin layer would not be observable from the surface, as it is only 1-2 % of the leached layer and the difference in colour and depth is minimal.

The total particle volume and calculated particle volumes for the 10 mm probe height samples are very similar. This indicates that the leached layer removed during ultrasonic cleaning with these parameters is almost entirely released as particles of 1-50 µm. However, it is clear from the spot size of the 25 s sample that the affected area is at least 1 cm in diameter. As such, it would be expected that here also a layer of the leached layer is removed, similar to the removal from the 40 mm probe height samples. However, it is not possible to attribute different particles to total and partial leached layer removal. Additionally, partial leached layer removal is difficult to determine with the current setup.

Nevertheless, a portion of the retrieved particles does not originate from the gaps left behind from the total leached layer removal. Therefore, the total volume of the remainder of the particles will be somewhat lower than the calculated volume. This difference is likely due to the porosity of the leached layer, which is not accounted for in the calculated volume or the particle volume of larger porous particles. Additionally, nanoparticles could also be generated, which sizes fall below the measurement limits of this methodology.

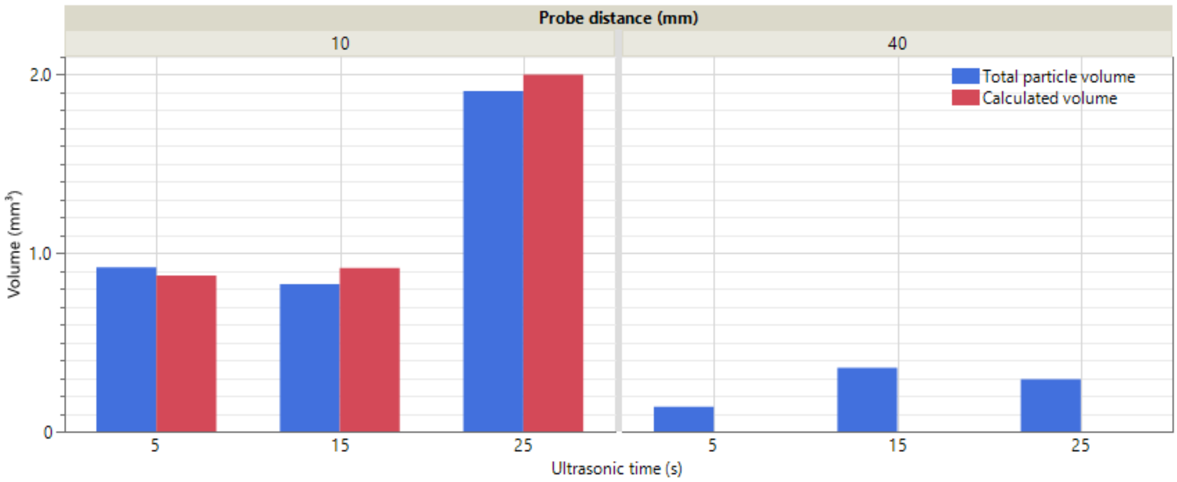


Fig.5: Comparison of volume as sum of all particle volumes from the automated SEM procedure, and as calculated from image and cross-sectional analysis.

5. Conclusion and outlook

Underwater ultrasonic cleaning of antifouling coatings can result in visible damage to the coating. This visible damage is due to the total removal of the leached layer. The removed portion of the leached layer is released as microplastic particles into the water. By reducing the intensity of cleaning, visible damage can be avoided. However, even without visible damage, microplastic particles are still released. The majority of particles released are smaller than 5 µm, but larger particles containing biocides and fillers are also released.

While ultrasonic cleaning is generally presented as a gentler alternative to traditional brush cleaning, coating damage and microplastic release are still possible. However, microplastic release from brush cleaning must also be investigated before concrete comparisons can be made. Furthermore, this work is limited to the coating used (a leached self-polishing coating). More testing is required to determine the microplastic release behaviour of different coatings and different coating technologies. The method presented in this work can be adapted to investigate microplastic release during cleaning using different cleaning techniques and coatings. Ultimately, this method could be employed to assist in finding a coating-cleaning combination that minimizes microplastic release, while still providing satisfactory fouling control.

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Advancing Global Understanding of Biofouling Control: A Collaborative Data-Gathering Initiative to Inform IMO Instrument Development

Mark Riggio, Ballastwater & Environmental Manufacturers' Association, Sedona/USA, techdirector@bwema.org

Abstract

The accumulation of biofouling on ships' hulls is a well-documented vector for the spread of aquatic invasive species (AIS), with significant ecological and economic implications. The International Maritime Organization (IMO) is progressing toward the development of a mandatory instrument to address biofouling management. In anticipation of this work item, the Ballastwater & Environmental Manufacturers' Association has launched a global Biofouling Research and Data Development initiative designed to support evidence-based policy formation. This paper outlines our approach and identifies six key questions we aim to answer through international collaboration with the scientific community, technology developers, vessel operators, ports, and regulatory authorities. We invite all interested stakeholders to participate in this critical research initiative.

1. Introduction

Biofouling, or the accumulation of aquatic organisms on wetted ship surfaces, is increasingly recognized not only as a driver of increased fuel consumption and maintenance costs but also as a primary pathway for the spread of AIS. To curb this threat, the IMO published the "2023 Guidelines for the Control and Management of Ships' Biofouling to Minimize the Transfer of Invasive Aquatic Species (2023 Biofouling Guidelines" or MEPC.378(80)), which provided voluntary guidance on the management of biofouling on ships' hulls and the "2025 Guidelines on Matters Relating to the In-water Cleaning of Ships' Biofouling" (MEPC.1/Circ.918) to provide voluntary guidance on how to properly clean ships' hulls once biofouling was found to have accumulated. However, the uneven implementation of these non-mandatory instruments and continuing risks of invasions have prompted calls for a mandatory instrument to ensure consistent global practices.

Recognizing the complexity of managing biofouling and the potential regulatory implications, the Ballastwater & Environmental Manufacturers' Association (BEMA) has launched a coordinated Biofouling Research and Data Development project (BRADD) to support the IMO's development of an effective, enforceable, and technically achievable framework. This paper outlines the six thematic areas of inquiry our project will investigate and identifies the types of data and expertise we are seeking from the maritime community in providing this critical, coordinated information to the regulatory process.

2. Body

The Ballastwater & Environmental Manufacturers' Association (BEMA) is an international, non-profit trade association representing equipment manufacturers, service providers, and stakeholders involved in shipboard environmental protection technologies, with a primary focus on ballast water management and biofouling remediation. BEMA advocates for science-based, technically achievable, and globally harmonized regulations that support effective environmental protection while ensuring operational feasibility for the maritime industry. Through collaboration with regulators, shipowners, and scientific experts, BEMA works to advance innovation, transparency, and performance in technologies designed to prevent the spread of aquatic invasive species and protect marine ecosystems.

As the primary non-governmental organization at the IMO representing not only hull cleaning equipment manufacturers, but also coating suppliers, biofouling additive manufacturers, equipment-based antifouling system manufacturers, and scientific test laboratories, BEMA is uniquely positioned to drive collaboration between stakeholders not only to identify the key questions ahead of the development of a mandatory instrument, but also to drive collaborative, science-based answers to these questions.

During work leading into the IMO's acceptance of work on a mandatory instrument at MEPC 83, BEMA identified six key questions that needed to be addressed in order to ensure that the new mandatory instrument was usable, enforceable, and science-based. These six key questions led to the identification of the need for external stakeholder inputs and assistance to develop a global, science-based data set which could be used by the various Administrations at the IMO to develop the mandatory instrument. These key questions, and their necessary input, are outlined in the following.

2.1. Cataloging the Existing and Emerging Technologies to Prevent Biofouling Accumulation

The first core objective of this initiative is to catalog and evaluate the technologies, products, and practices currently available—or in development—that aim to prevent or minimize biofouling on ships. While a primary focus of the work at the IMO to date has been relating to the inspection of hulls and the cleaning of biofouling once observed, BEMA feels that it is critically important to identify technologies and best practices that can prevent the initial accumulation of biofouling.

These technologies include:

- Coatings and Additives: We seek data on the performance of novel antifouling coatings, foul-release coatings, and hybrid systems. Information on formulation innovations, such as bio-based or nanomaterial additives, as well as new application or curing processes, is critical to assess practicality and scalability.
- Non-Coating Solutions: Beyond paints, we aim to document non-coating antifouling systems (AFS), including ultrasonic technologies, air bubble systems, and robotic hull-sheathing. We seek operational data from vessels that have implemented these systems, particularly in varied salinity and temperature zones.
- Marine Growth Prevention Systems (MGPS): MGPS are commonly used in sea chests and cooling intakes but may play a broader role in deterring initial settlement of fouling organisms. We aim to validate MGPS effectiveness with respect to hull surfaces and identify methods for quantifying their contribution to biofouling control.

2.2. Assessing the Risk Posed by Microfouling

The role of microfouling—biofilms and microbial slimes—in invasive species transfer remains under-studied. Further, while there is little doubt that invasive microorganisms are present in the environment, the subset of organisms which make up biofouling (organisms capable of attaching to a ships' hull and surviving a transit still attached to the hull) may have different environmental risks than the whole suite of microorganisms which are present in ballast water. BEMA therefore feels it is also critically important to understand the scientifically based risks of biofouling through studying the following factors:

- Biodiversity of Slime-forming Organisms: We are collecting information on the makeup of organisms that are present in bioslime at the various different ports in the world to compare the makeup in different areas to determine the relative ubiquity of biofilm-forming organisms. This can help us to determine both the risk of invasion and also, potentially, map where new invasions may become practical due to climate shifts.
- Invasiveness and Detachment: We are collecting evidence on whether microfouling detaches naturally in port environments without external cleaning and whether the organisms within biofilms have a demonstrated capacity to colonize new environments once detached, naturally or through cleaning, from the hull.

- Ecological Risk: Collaboration with marine biologists and ecologists is needed to evaluate the reproductive and survival potential of microfouling organisms post-detachment following cleaning or following cleaning with some form of disinfection.

These findings will inform whether microfouling, and particularly the frequent cleaning of microfouling from ships' hulls without capture as part of a hull performance optimization program should be explicitly addressed in regulatory instruments and what monitoring thresholds may be necessary.

2.3. Evaluating the Risks of Cleaning Without Capture

In-water cleaning practices vary widely across jurisdictions, with inconsistent requirements regarding effluent capture and environmental discharge but the frequent cleaning of ships' hulls for the improvement of performance, known as hull grooming, is a desired practice by ship owners. There is also a significant risk that localized regulations and regulatory barriers may force all cleanings to be done in ports with less regulatory burden, shifting the risks of bio-invasions to countries and areas with less ability to cope with the environmental damage.

As the IMO's mandatory instrument will be a vehicle to ensure that there is equal access to cleaning areas globally, BEMA wants to study a number of key items relating to the cleaning of microfouling without capture to help ensure that the regulatory process is based on scientific evidence rather than perception. BEMA seeks information on:

- Paint Release During Cleaning: We are investigating how much coating is released during microfouling-only cleaning operations, and how this compares with passive release from vessels at anchor, during transit, or while idle in port.
- Survivability and Reattachment: We are seeking experimental data and case studies that demonstrate whether biofouling organisms detached from hulls can survive and reattach to nearby surfaces—particularly in high-traffic or environmentally sensitive ports.
- Local Cleaning Areas: During anchorage or lay-up, many vessels experience localized biofouling buildup. We seek feedback from operators and cleaning service providers on the practicality and risk of cleaning under these circumstances. Further, we seek more information and case-studies about the different types of cleaning areas available and the risks or benefits of each type, including cleaning at sea while drifting or underway, cleaning at anchorage, cleaning at the berth, or cleaning offshore prior to entry into port.

We aim to establish a clearer risk profile for the complete or partial cleaning of ships without capture and to define the thresholds at which cleaning without capture becomes environmentally unacceptable.

2.4. Determining the Best Achievable Rates of Treatment and Capture

To support effective regulation, it is critical to understand what levels of biofouling removal and effluent treatment are currently achievable using commercially available technologies.

- Capture Efficiency: We are seeking data on standardized methodologies to measure capture rates and the proportion of cleaning effluent returned to the surrounding environment.
- Effluent Treatment: Innovations in treatment technologies—including filtration, UV, chemical dosing, and centrifuge systems—will be evaluated for their ability to neutralize viable organisms and remove harmful solids and inorganics from collected waste.
- Measurement of Capture of Microfouling: We are further seeking data on standardized methodologies to measure the amount of microfouling captured or released during cleaning of macrofouling with capture. Current practices for measuring capture rates are based solely on the capture of macrofouling which creates a dual standard between the perceived lack of capture for systems that only clean microfouling and have no capture ability.

Through partnership with service providers and port authorities, we will identify best practices and recommend technology- and performance-based standards based on the best technologically achievable performance of both existing equipment and the foreseeable technological advancements.

2.5. Assessing Paint Compatibility and Defining Damage

One of the most critical concerns for vessel operators is whether in-water cleaning—especially mechanical cleaning—is compatible with existing hull coatings. BEMA is committed to taking part in the development of universal compatibility standards that take into account:

- Definition of "Coating Damage": We aim to create a standardized framework for defining coating damage, which may include physical abrasion, chemical breakdown, or loss of antifouling function. Differentiating between cosmetic and functional damage is essential.
- Diversity of Paint Types: The diversity of hull coatings in use globally complicates universal compatibility claims. We are working to develop ways to cataloging cleaning compatibility testing data across a representative sample of coating types and brands to assess general trends and outliers and to provide a science-based approach to assessing compatibility through data analysis rather than requiring extensive testing across multiple types of hull coatings.

This work is crucial for establishing protocols that balance effective fouling removal with preservation of coating integrity and long-term performance. BEMA understands that while cleaning of macrofouling may have an inherent impact on coatings, it should be the goal of all biofouling remediation to keep the hull antifouling coating system as intact as possible to ensure the prevention of future accumulation of biofouling.

2.6. Understanding Global Capacity for Cleaning with Capture

During the development of the voluntary guidelines, it has been established that the cleaning of microfouling without capture is acceptable. Capture is only required if there is macrofouling present. If the new mandatory IMO instrument requires all cleaning to be done with capture, the global infrastructure must be ready to support it. As the primary representative of the cleaning industry, BEMA is looking to provide information to the regulatory process on:

- Service Providers and Technology Availability: We are compiling an inventory of commercial cleaning services that offer capture-based solutions, segmented by region, port access, and technological method. Additionally, we are compiling an inventory of commercial cleaning services that offer non-capture cleaning of microfouling as well as non-capture cleaning of macrofouling, which is not allowed under the current voluntary guidelines.
- Permit and Reporting Practices: Regulatory requirements for cleaning operations differ based on location—port, anchor, or at sea. We are evaluating how permits are issued, who governs them, and whether previous cleaning reports are accepted between ports.
- Estimating Service Providers and Technology Scaling Abilities: BEMA also plans to study and model the potential for existing service providers and technology providers to scale up based on both a full-capture model and a microfouling-only cleaning without capture model. Each of these scaling exercises can help inform the IMO about potential implementation windows and timelines for shifting to increasingly protective standards.

Establishing a global baseline of available capacity by cleaning type is critical to understanding the ability of the maritime industry to meet the requirements of any new mandatory instrument. Having the equipment and service providers to conduct the mandatory inspections and cleanings is essential for the implementation of practical and enforceable regulations.

3. Conclusion

The IMO's development of a mandatory biofouling management instrument represents a pivotal moment in maritime environmental protection. However, its effectiveness will depend on a robust foundation of practical, scientific, and operational data, and its implementation will depend on the benefit ships can receive from the frequent cleaning of the main areas of the hull to improve performance and reduce fuel consumption. BEMA's data-gathering initiative is designed to fill current knowledge gaps and guide policy with science-based information, practical data, and inclusivity.

BEMA invites stakeholders from all sectors—shipowners, port authorities, technology developers, regulators, and academics—to contribute data, share case studies, and participate in pilot assessments. Only through a broad collaboration can we develop a regulation that is globally implementable, environmentally protective, and operationally viable.

Acknowledgement

We thank all the participating institutions and stakeholders who have provided insight and guidance to date including BEMA members Alicia Bots, Biomarine Services, CRABI Robotics, Echo Tech Marine, Fleet Robotics, GIT Coatings, Greensea IQ, I-Tech, Jotun, Shipshave, and Subsea Global Solutions. We look forward to expanding this coalition in the months to come.

Implementation and Evaluation of Laboratory-Scale Strategies for In-Water Cleaning of Fouling Control Coatings

Pascal Guth, CoaST, Technical University of Denmark, Lyngby/Denmark, pasgu@kt.dtu.dk
Huichao Bi, CoaST, Technical University of Denmark, Lyngby/Denmark, hubi@kt.dtu.dk
Kim Dam-Johansen, CoaST, Technical University of Denmark, Lyngby/Denmark, kdj@kt.dtu.dk

Abstract

This study introduces laboratory-scale devices designed to simulate in-water cleaning of fouling control coatings under controlled conditions. Three cleaning methods — brush, ultrasonic, and water-jet — are shown, each enabling the evaluation of cleaning performance, coating degradation, and environmental release. The custom-built setups allow precise control and monitoring of cleaning parameters like force, motion and speed. Semi-automated image processing eases detailed comparisons of cleaning efficiency. These tools provide valuable insights to optimize cleaning strategies, prolong the lifetime of fouling control coatings and support the development of coatings engineered for durability under routine in-water cleaning tasks.

1. Introduction

Marine biofouling, defined as the accumulation of microorganisms, algae, and marine animals on submerged surfaces, forms a persistent and substantial challenge for the maritime industry, *Yebra et al. (2004)*. When biofouling accumulates on a ship's hull, it can have several adverse effects, including increased hydrodynamic drag leading to greater fuel consumption resulting in elevated greenhouse gas emissions, *Qui et al. (2022)*. Furthermore, it plays a significant role in the dissemination of invasive aquatic species by acting as a carrier for their transportation across ecosystems, *Hopkins et al. (2010), Coutts et al. (2003)*. To mitigate the above-mentioned impacts, in-water hull cleaning has become an essential maintenance practice, allowing for the removal of biofouling without the need to bring vessels into dry docks, *Song et al. (2020), Oliveira et al. (2022), Kim et al. (2025)*.

Although full-scale, in-water cleaning is essential for managing biofouling on an actual ship hull, analyzing existing and new technologies in operational settings remains a significant challenge, *Wu et al. (2022)*. Field testing is often limited by environmental variability, high costs, and complex regulations, *Basu et al. (2020)*. These factors make isolating cleaning performance variables and the actual environmental impact more difficult. Laboratory-scale testing is an effective and practical approach for the preliminary assessment, improvement, and optimization of in-water cleaning strategies, overcoming these limitations, *Wu et al. (2022)*.

Laboratory-scale in-water cleaning devices are an important addition to full-scale field trials. These devices offer a clear advantage in developing an improved understanding of in-water cleaning technologies, *Scianni et al. (2019)*. In a controlled laboratory environment, cleaning methods can be tested systematically under consistent and repeatable conditions that closely mimic a real marine environment, *Lin et al. (2023)*. These experiments are crucial for optimizing cleaning performance, evaluating effectiveness and identifying potential limitations, *Lin et al. (2024)*.

Additionally, laboratory testing also enables careful monitoring of environmental aspects, such as the amount of biocide released by a cleaning method and the unintentional spread of species during cleaning. This level of detail allows more accurate environmental assessments and enables the evaluation of each cleaning approach alongside a range of hull coating systems, *Weber et al. (2023)*. These assessments ensure safety, effectiveness and compliance with environmental limitations. Laboratory-scale research can therefore support the development of best practices for cleaning frequency and parameters, ensuring alignment with international standards and environmental protection goals.

2. Controlled exposure of fouling control coatings

The CoaST Maritime Test Centre (CMTC) for field exposures, Fig.1a, is located in the Baltic Sea at Hundested Harbour in North Zealand, Denmark. This location offers representative temperate marine conditions, including seasonal variation and natural biofouling pressure, *Pedersen et al. (2023)*. Sensor technologies are employed to continuously monitor environmental conditions contributing to the observed fouling pressure during the exposure period. These included key water quality parameters such as temperature, salinity and dissolved oxygen, as well as general weather conditions (e.g., air temperature, solar radiation, rain fall). Tracking these variables supports contextual interpretation of coating performance alongside fouling intensity and ensures comparability between field and laboratory exposures.

At the CMTC, samples can be exposed under two distinct regimes:

- Static exposure: Panels can be mounted on a cartridge under static conditions to simulate idle or lay-up conditions of vessels, Fig.1c.
- Dynamic exposure: Samples can be mounted on a rotor test system that is able to replicate relative water velocities corresponding to vessel speeds ranging from 6 to 30 knots, Fig.1b.

In parallel, duplicate samples can be subjected to equivalent static and dynamic conditions in a controlled laboratory setting using artificial seawater. These laboratory exposures prevent the development of marine biofouling and enable a focused assessment of coating aging and changes in surface properties, such as matrix degradation or leaching effects, without interference from biofouling formation. This dual-exposure strategy enables a comparative evaluation of both antifouling performance and intrinsic material durability across coating types. Furthermore, it allows systematic testing of cleaning efficiency using various laboratory-scale in-water cleaning setups with samples having marine biofouling to analyse cleaning efficiency while also being able to track surface damages or changes due to cleaning strategies without interference of fouling. The controlled laboratory conditions support detailed assessment of how different cleaning methods affect surface properties and material release from each coating type.

Visual inspection together with imaging and image analysis allows analysing the fouling growth rate on the panels, monitor cleaning efficiency by measuring the area of removed fouling and also analysing surface damages caused by cleaning procedures.

Fig.1: a) CoaST maritime test centre (CMTC) allowing for field exposure in the Baltic Sea under b) dynamic conditions with a rotor setup and c) static conditions

3. Laboratory scale in-water cleaning

To evaluate the performance and impact of different in-water cleaning strategies under controlled conditions, a series of laboratory-scale systems were developed and customized. These setups enable systematic testing of cleaning forces, surface interaction, and environmental variables across a range of fouling control coatings. The systems are modular and adaptable, allowing the simulation of three distinct cleaning methods — brush, ultrasonic, and water-jet cleaning — while maintaining consistent sample handling and measurement protocols.

3.1. In-water brush cleaning

An automated in-water cleaning system (AUCS) was developed to simulate in-water brush cleaning under controlled laboratory conditions, Fig.2, *Lin et al. (2023)*. The system consists of a water tank in which coating samples can be securely fixed. Depending on the experimental requirements, the water level within the tank can be adjusted and filled with real seawater, artificial seawater or other test liquids.

The experimental setup consists of a modified X-Y-Z aluminum mechanical gantry system, originally based on the OPENBUILDS Lead CNC (1000 × 1000 mm), but adapted to dimensions of 690 mm (X), 800 mm (Y), and 300 mm (Z). The gantry is controlled via G-code using OpenBuilds CONTROL software. Prior to each cleaning procedure, the Z-carriage is resetted to the origin point (0, 0) to ensure standardized starting conditions. An integrated NEMA23 servo motor (180 W) is mounted on the Z-carriage to provide brush rotation. This motor, connected via a coupling mechanism, allows quick replacement of brush types. The motor operates reliably within a calibrated speed range of 400 rpm to 1100 rpm, suitable for the system's cleaning requirements.

A custom-built water tank made from 10 mm thick transparent polycarbonate panels (internal dimensions: 765 × 375 × 80 mm) is securely mounted to the gantry base using specially designed adapters. The tank features a drainage outlet for seawater removal post-cleaning. Inside the tank, sample holders are positioned, allowing for the secure attachment of test panels. To prevent splashing and contamination of the gantry system, two tank lids are installed.

A digital force sensor (Model 1022, Lidén Weighing, Sweden) is integrated between the motor and the Z-carriage to measure the normal force applied during cleaning. Real-time force data is recorded at a sampling rate of 10 Hz using the VS3 software from Lorenz Messtechnik GmbH. Before each cleaning procedure, the sensor is zeroed to ensure that the recorded force starts from 0 N; so once the brush makes initial contact with the surface the reading starts.

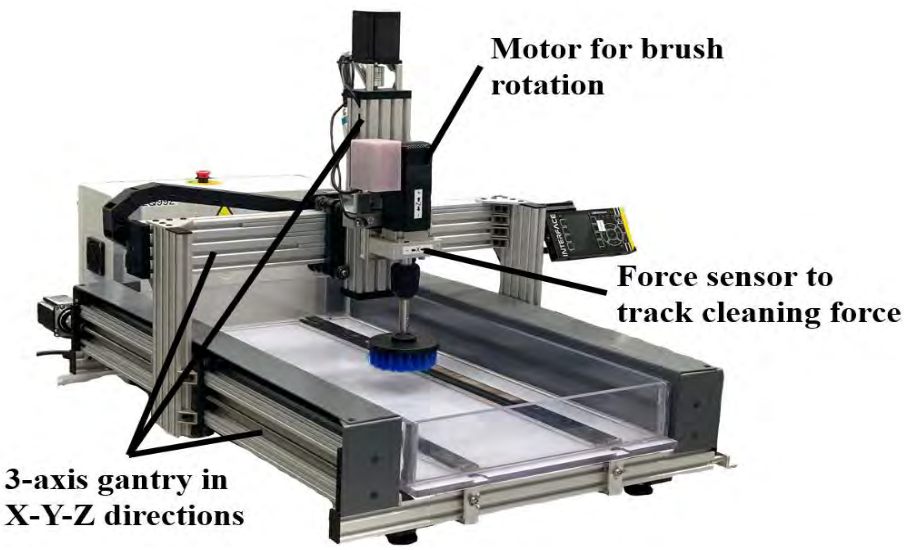

Fig.2: AUCS for laboratory-scale brush cleaning, with 3-axis gantry for controlled movement within the water tank and integrated force sensing for monitoring cleaning forces

3.2. In-water ultrasonic cleaning

The AUCS, originally designed for brush-based cleaning, can be adapted to accommodate an ultrasonic transducer in place of the brush, Fig.3a. In this configuration, the system also includes a water tank that securely holds coating samples for testing. The water level in the tank is adjustable as well and it can be filled with real seawater, artificial seawater, or other test fluids depending on the specific experimental requirements.

The tank and gantry setup closely resembles the in-water brush cleaning system described in Section 3.1. The z-axis allows fine adjustments in 0.1 mm increments, enabling precise control of the distance between the sonotrode and the sample surface. Various sonotrodes can be mounted on the ultrasonic transducer, allowing the investigation of different geometries and sizes to evaluate their effects on cleaning efficiency, coating integrity, and overall performance, Fig.3b–c. The ultrasonic transducer operates at a fixed frequency of 26 kHz, with oscillation amplitude ranging from 9 µm to 90 µm based on the sonotrode. It supports both continuous and pulsed operation, with adjustable on-off cycle durations.

The system also provides real-time power output readings, making it possible to measure the energy consumption of each cleaning process. These values offer insight into the energy required to remove biofouling from different surfaces and can be interpreted in a similar context to the brush cleaning force.

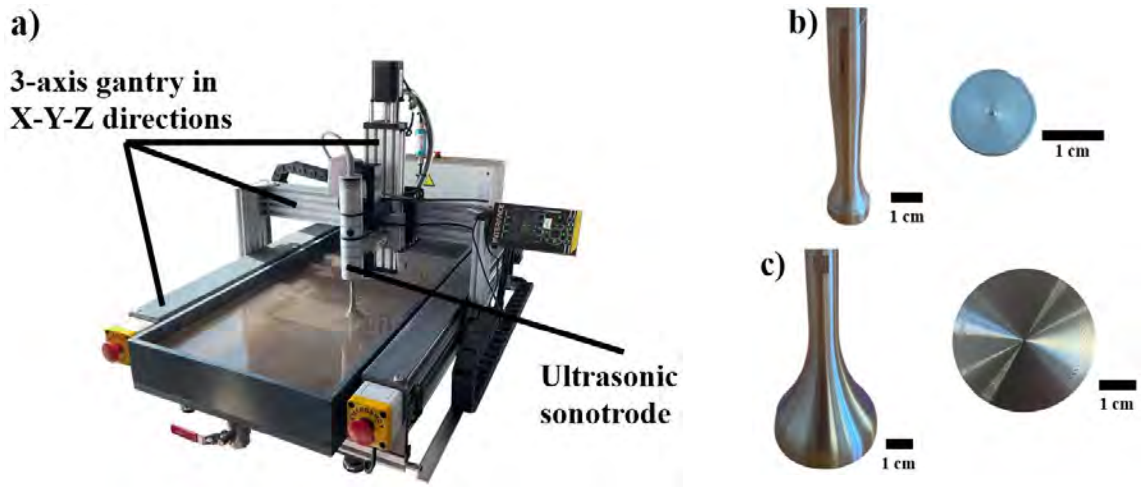

Fig.3: AUCS for laboratory-scale ultrasonic cleaning, equipped with a 3-axis gantry for precise movement within the water tank, b) small ultrasonic sonotrode geometry, c) large ultrasonic sonotrode geometry

3.3. In-water water-jet cleaning

The in-water water-jet system was developed to simulate and analyze water-jet cleaning in submerged conditions. It includes a water tank that can be filled with real seawater, artificial seawater, or other test fluids. An integrated overflow system maintains a constant water level even during continuous water inflow, ensuring stable conditions and consistent force sensor readings during cleaning tests.

The sample holder is designed for flexibility and user convenience. It can be retracted from the tank, Fig.4, for easy sample mounting and adjustment. While retracted, the distance between the nozzle and the sample surface can be set, and the holder allows the nozzle to be angled toward the substrate, enabling testing under different nozzle-to-surface orientations.

A submersible force sensor is positioned beneath the sample holder to measure the water jet's impact force. During operation, it records real-time impact data, providing precise measurements of the forces applied to the surface. The cleaning duration is also precisely controlled.

The system supports interchangeable nozzle heads, allowing tests with different nozzle geometries to assess their effect on cleaning performance. Both water pressure and flow rate can be adjusted. In addition to static spot testing, the nozzle can be moved laterally across the sample. The integrated force sensor captures dynamic force data during movement, enabling a thorough assessment of cleaning effectiveness and surface loading across the entire test area.

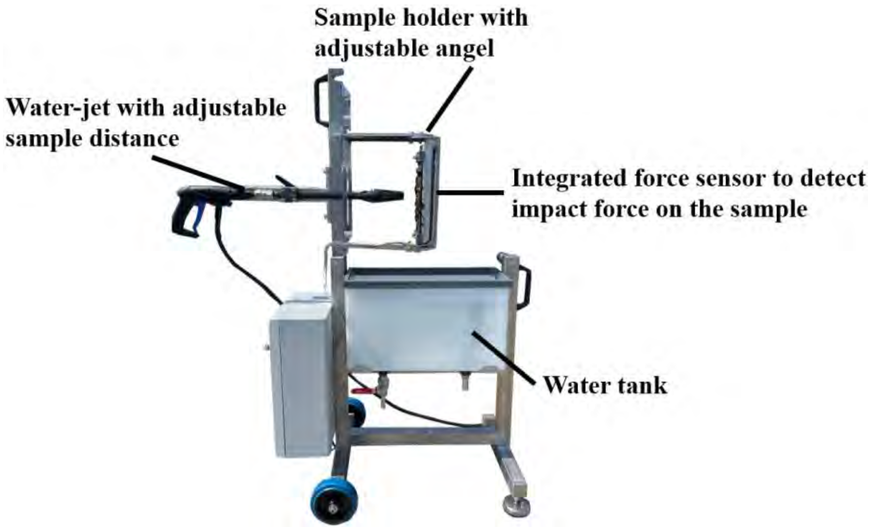

Fig.4: In-water water-jet cleaning device with adjustable nozzle angle and distance to sample surface

4. Results and Discussion

To evaluate fouling coverage before and after laboratory-scale in-water cleaning, a semi-automated image analysis workflow was implemented using a combination of Python scripting and ImageJ plug-ins. As illustrated in Fig.5a–5c, the original images were converted into 8-bit grayscale format, enabling threshold detection of fouled areas. Based on this threshold, fouling coverage could be quantified either as a percentage or as an absolute area measurement.

Fig.5d–5l show representative results from laboratory-scale in-water cleaning tests using three distinct methods: brush cleaning, ultrasonic cleaning, and water-jet cleaning. These comparative images demonstrate the cleaning effectiveness of each method and reveal potential surface damage to a commercial antifouling coating following in-water cleaning. For each method, at least two parameter settings were tested, revealing variable removal rates based on the cleaning method and its parameters.

In addition to cleaning efficiency, surface condition was also evaluated to identify coating damage. For enhanced visibility of damage patterns, post-cleaning images were adjusted in terms of their saturation. The results show that all tested cleaning techniques can introduce some degree of damage to an antifouling coating. However, the laboratory-scale systems enables controlled testing and can therefore help define method-specific performance limits and sensitivities. These insights can inform the best operational practices on ships, aiding in the selection of cleaning parameters that maintain coating integrity and prolong the service life of fouling control coatings.

The type and extent of damage observed varies by cleaning method. Brush cleaning was found to cause visible surface scratching when excessive force was applied, consistent with bristle contact, Fig.5c, *Lin et al. (2025)*. The extent of damage ranging from superficial scratches on the surface to full removal of the coating in severe cases. Ultrasonic cleaning produced more uniform surface wear, with partial to full removal depending on the cleaning parameters, Fig.5f. Water-jet cleaning led to partial superficial erosion, Fig.5i, with the potential for full coating removal at high impact forces.

These observations underscore the importance of tailoring both cleaning strategy and coating design to ensure effective fouling removal while minimizing long-term material degradation.

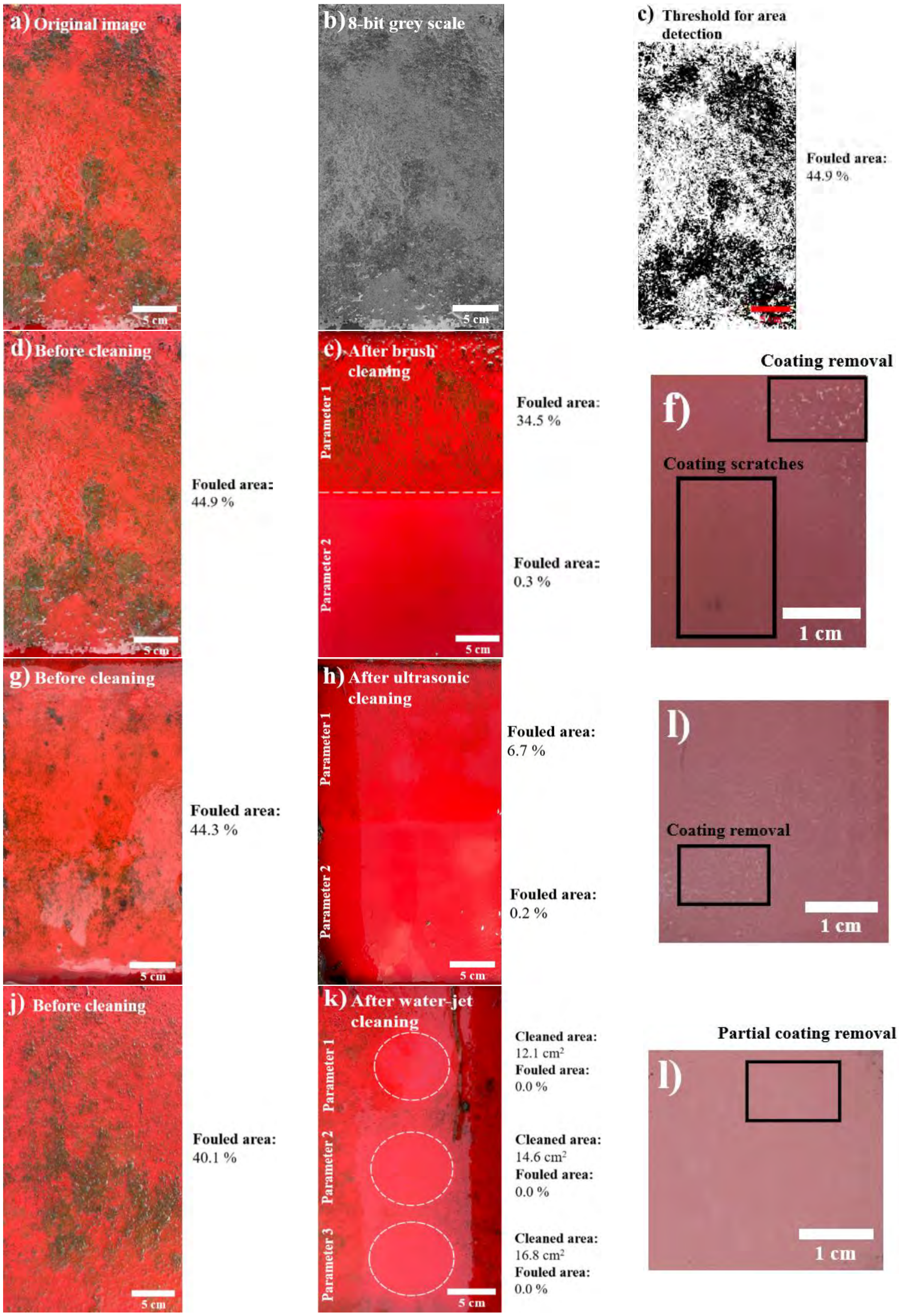

Fig.5: Commercial antifouling coating samples with fouling after field exposure, shown before and after laboratory-scale in-water cleaning using three different methods; a)-c): Image processing for area detection, d)–f): Brush cleaning, g)–i): Ultrasonic cleaning and j)–l): Water-jet cleaning

5. Conclusion and Outlook

Laboratory-scale testing not only reveals the operational limits of current in-water cleaning technologies but also enables the adjustment of cleaning parameters to better meet the needs of specific end users. This adaptability is essential for optimizing performance while minimizing unintended coating damage.

Looking ahead, such controlled testing environments can play a pivotal role in guiding the development of a new generation of fouling control coatings — engineered not only to resist fouling but also to withstand and even complement specific cleaning methods. By tailoring coating properties to match cleaning techniques, future solutions can achieve greater durability and cleaning compatibility, supporting more frequent and efficient in-water maintenance for a prolonged fouling free surface.

Importantly, the controlled laboratory conditions allow precise monitoring of material release during cleaning operations. This includes not only fouling residues but also potential biocide emissions from fouling control coatings. The integration of suction-based capturing systems into the test setups further enables the evaluation of collection efficiency by comparing retained residues in the tank with those recovered through suction. These capabilities provide valuable insight into the environmental footprint of cleaning processes and support the development of mitigation strategies to reduce ecological impact — critical for the future of sustainable and compliant hull maintenance practices.

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Field Validation of Proactive Robotic Hull Cleaning: Advancing Fuel Efficiency, Emissions Reduction, and Environmental Compliance

Tom Loefler, Hullbot, Rozelle/Australia, tom@hullbot.com
Ben Dwyer, Hullbot, Rozelle/Australia, ben.dwyer@hullbot.com
Anna van Nieuwland, Hullbot, Rozelle/Australia, anna@hullbot.com
Steve Winnall, Hullbot, Rozelle/Australia, steve.winnall@hullbot.com

Abstract

As robotic hull cleaning becomes increasingly recognized as a vital and positive advancement, industry best practices are shifting toward a comprehensive, holistic approach. Today, effective hull cleaning means balancing regulatory demands, client expectations, and environmental responsibility. By cleaning at regular intervals with an advanced, gentle robot, operators can consistently remove only early-stage microfouling, improving vessel efficiency while minimizing both invasive species transfer and the potential for coating damage. This integrated approach, combines antifouling coatings, robotic cleaning, digital monitoring, and data analysis, improves hull performance and minimizes operational disruptions. To evaluate these practices, field data has been collected from deployments over 8 global locations, covering 900 commercial cleaning operations across 40 unique vessels (passenger, fishing, shipping) and 5 unique classes of hull coatings (Silicone FRC, FRC+biocide, SPC, hard epoxy, soft ablative). This study presents findings from Hullbot, an in-water, proactive robotic cleaning system designed to enable frequent, gentle hull cleaning with real-time digital tracking. Results show that regular hull cleaning reduces hull roughness, delivering fuel savings and greenhouse gas emission reductions up to 26%, while also increasing vessel uptime and extending coating lifetimes. Hullbot has validated the reduction of over 1,000,000 L marine diesel to date, currently saving 141,000 L per month, equating to 3,100,000 kg CO2e emissions reduced. Third-party validation of Hullbot's in-water cleaning methods showed compliance with IMO, DAFF, and U.S. EPA water quality guidelines. Independent testing by the Australian Defence Science and Technology Group (DSTG) confirms that this method is compatible with all major hull coatings. Five-year simulations showed only 5–10 µm removal from soft ablative coatings, and only temporary elastic changes for silicone FRC coatings. In-water field testing showed that cleaning operations did not cause any statistically significant increase in total suspended solids (TSS), copper, or zinc concentrations. These results support that in-water cleaning, at macrofouling levels <2, does not negatively impact water quality.

1. Universal presence of slime: A continuous ongoing reality for all hull coatings and vessels

1.1. Slime grows globally on highly active vessels with all types of coating

Hullbot has inspected and cleaned sections of 29 vessels coated with silicone foul-release coatings (FRCs) across a diverse range of geographies, including Sweden, Norway, Denmark, New Zealand, Japan, Mexico, Spain, Australia, New Zealand and the United States. Slime and biofilm accumulated on all vessels Hullbot has inspected, across every antifouling type and coating system, no matter how frequently or intensively they operate, including those with high-performance silicone FRC coatings. Every vessel presented with biofouling, and in some cases macrofouling, demonstrating the universal need for proactive maintenance on all coatings, including advanced coatings.

Hullbot's system has also been deployed on vessels coated with Hempel X7, Intersleek 1100SR, and PPG Sigmaglide, as well as on more traditional coating types such as self-polishing copolymers (SPCs), ablatives, and exotic coatings such as hard epoxy coatings. This is a global, persistent reality, even for high-speed passenger vessels that operate 7 days per week, with the highest coating standards. Certain vessels with regular weekly in-water hull grooming developed significant observable slime between less than weekly cleans, Fig.1 (slime levels on various ships globally).

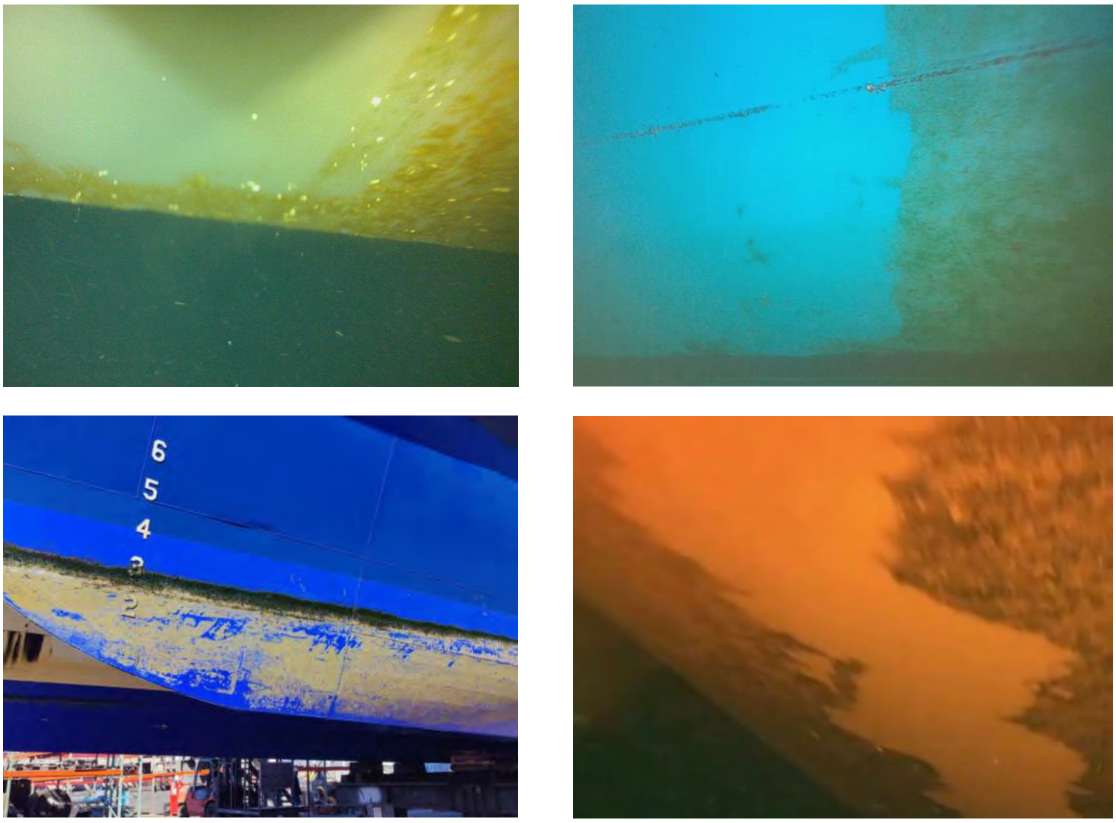

Fig.1: (Top left) Three days of slime growth on a vessel cleaned twice weekly. (Top right) Hullbot cleaning a silicone FRC coating on a high-activity, fast vessel in warm water. (Bottom left) Slime covering a silicone FRC coating on a high-activity, fast vessel in cold water. (Bottom right) Intersleek 1100SR after two years in service on a high-activity, fast vessel in cold water.

Even among highly active vessels on consistent high-frequency routes, such as Sydney's NRMA-operated fast ferries, Fig.2, slime accumulation has been consistently observed. The route between Circular Quay and Manly runs from 6:15 am to 9:15 pm, with some 40 departures each way daily. Intense operational schedules and monthly cleaning are not sufficient to fully prevent biofouling, highlighting a persistent challenge that coatings alone cannot address and the need for supportive grooming.

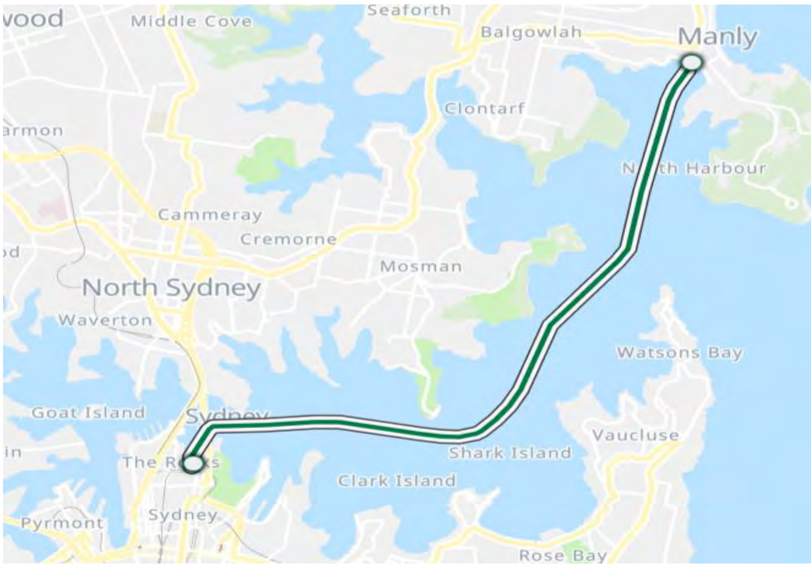

Fig.2: Daily consistent routing of NMRA vessels between Circular Quay and Manly

1.2. Removing Slime Saves Fuel

Analysis of operational data shows that maintaining slime-free hulls through regular in-water grooming leads to improved vessel performance and significant fuel savings, with customers reporting reductions between 9% and 26% across different coating types. This is compared to a business-as-usual baseline which in many cases includes frequent proactive cleaning with divers already.

Table I: Cleaning Data by Coating Type: Number of Operations and Impact of Slime Removal

Coating	Number of Vessels	Number of Cleans	Fuel Efficiency
Epoxy	5	394	11% - 17%
Silicone FRC	26	322	7% - 26%
Traditional ablative	5	48	9% - 14%
Hard biocidal	2	32	10%

2. Hull grooming does not damage coating, validated by field & third-party testing

2.1. Gentle proactive grooming extends coating lifetime

Hullbot has performed nearly 400 in-water cleanings of silicone FRCs without causing coating damage, and across more than 900 cleans on various coatings, no damage has ever been observed. Proactive grooming has, in some cases, been shown to extend coating lifespan, Fig.3. Adjustable cleaning speed, brush type, and pressure allow compatibility across a wide range of hull coatings, supporting flexible maintenance strategies within diverse fleets. Over 22 months of continuous cleaning on FRC-coated hulls confirms that proactive grooming can deliver optimal performance and sustained biofouling control. These findings indicate that regular, gentle cleaning practices can reduce reliance on toxic antifouling coatings, helping the industry move towards more sustainable solutions.

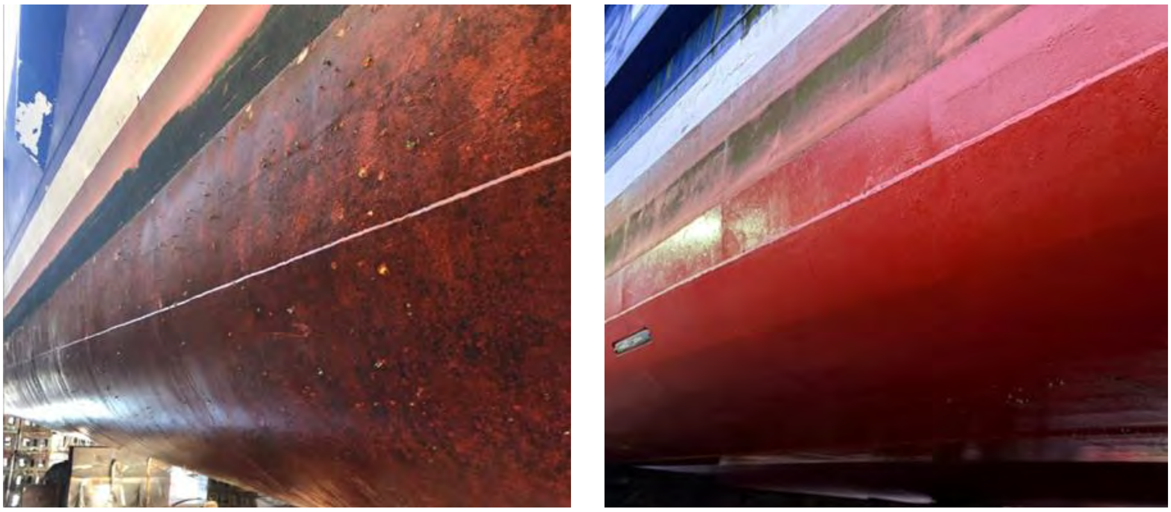

Fig.3: Hull condition upon yearly dry docking (Left) One year without/before Hullbot, extensive macrofouling is evident (FR 20–FR 30 condition). (Right) After one year with Hullbot, a non-biocidal coating remains 100% free from macrofouling.

Every cleaning operation is thoroughly documented using high-definition 1080p photos and videos captured by on-board cameras, Fig.4. This extensive visual record allows detailed monitoring of fouling and coating conditions, providing objective evidence of the effectiveness of proactive grooming. Consistent photographic documentation supports early detection of biofouling and enables timely interventions to help extend the lifetime of antifouling coatings.

Fig.4: Documentation of every operation per vessel, enabling comprehensive records and detailed reporting of coating conditions and changes over time

Fig.5: Side-by-side hull fouling after one month in San Francisco Bay. One side cleaned just before haul-out, the other not cleaned for a month.

2.2. Third-party independent field testing of water quality during in-water cleaning

Third-party field assessments have shown that in-water robotic hull grooming can be safely conducted without impacting water quality. Operational cleaning events, such as those in Sydney's Darling Harbour, included sampling for total suspended solids (TSS), copper, and zinc before, during, and after cleaning at distances ranging from 1 to 50 m and on days before and after the operation, Fig.6. Testing was managed by independent environmental consultants, with laboratory analysis by accredited facility Envirolab Services. Results showed no statistically significant increases in any contaminants, with all values either below detection limits or within natural background variation, Fig.6. These findings confirm that port-based cleaning meets environmental thresholds set by Australian Department of Agriculture, Fisheries and Forestry (DAFF) and IMO in-water cleaning guidelines.

Dataset	Mean	variance	p-value	n
Copper				
Ground Truth	3.56 µg/L	4.12	0.3604	24
Cleaning	2.56 µg/L	4.53	0.3604	27
Zinc				
Ground Truth	7.75 µg/L	2.80	0.0001	24
Cleaning	5.81 µg/L	2.08	0.0001	27
TSS				
Ground Truth	5.46 mg/L	0.77	0.5331	24
Cleaning	5.67 mg/L	2.15	0.5331	27

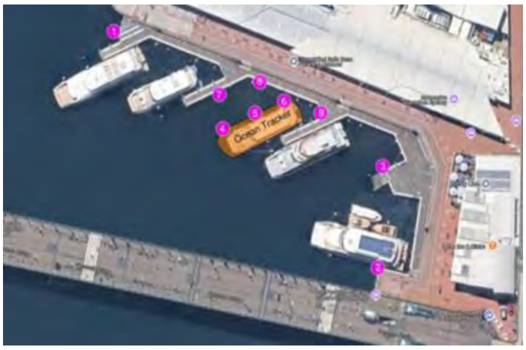

Fig.6: Water testing results and mapped locations of sample collection sites

2.3. DSTG laboratory accelerated life testing

An accelerated life testing program was developed with the Australian Defence Science and Technology Group (DSTG) to assess the long-term impact of continuous robotic grooming on hull coatings, Fig.7. The system simulated five years of weekly cleaning within eight hours, testing two coating types: a soft ablative system and a silicone foul-release coating. Material removal on the ablative coating was only 5–10 microns, within measurement error, indicating no significant degradation. The silicone coating showed a minor, elastic thickness change that fully recovered after cleaning, with no change to the biocide content confirming maintained efficacy. These results demonstrate that robotic grooming, when performed at appropriate intervals and pressures, is compatible with modern hull coatings for long-term maintenance.

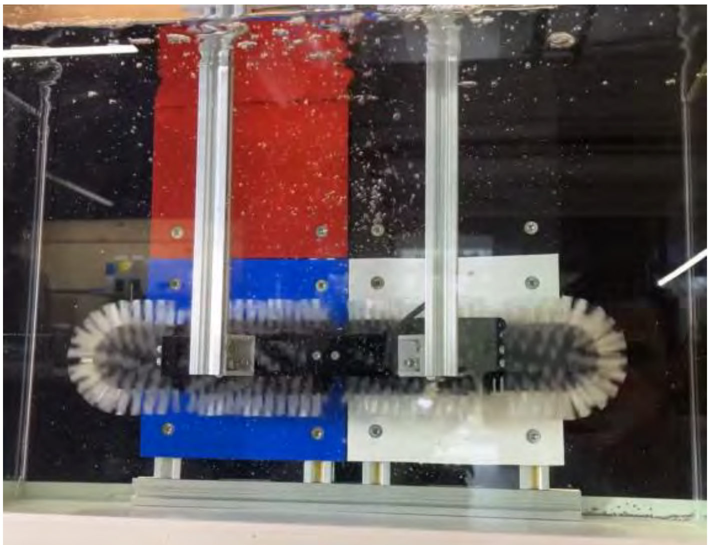

Fig.7: DSTG testing program

3. Fast deployment speed, versatility, and free-swimming autonomy

Recent advances in in-water hull cleaning technology have demonstrated effectiveness across diverse regions, under a range of water temperatures and fouling conditions. Operational datasets now include major ports with varying biofouling rates and water qualities. A new generation of compact, brush-equipped robots is enabling more consistent, safe, and efficient hull maintenance for aluminum fast craft, vessels with complex hull geometries, and premium silicone coatings. These autonomous platforms utilize adaptive brush technologies and digital tracking to optimize cleaning pressure and technique for each surface and coating. Operators can now be supported by decision frameworks that consider vessel configuration, operational patterns, and regulatory requirements, facilitating proactive and tailored maintenance strategies. Integration with port and fleet management systems further streamlines scheduling, compliance, and data management. Routine cleaning and inspections are digitally documented, establishing comprehensive maintenance and compliance records for each vessel.

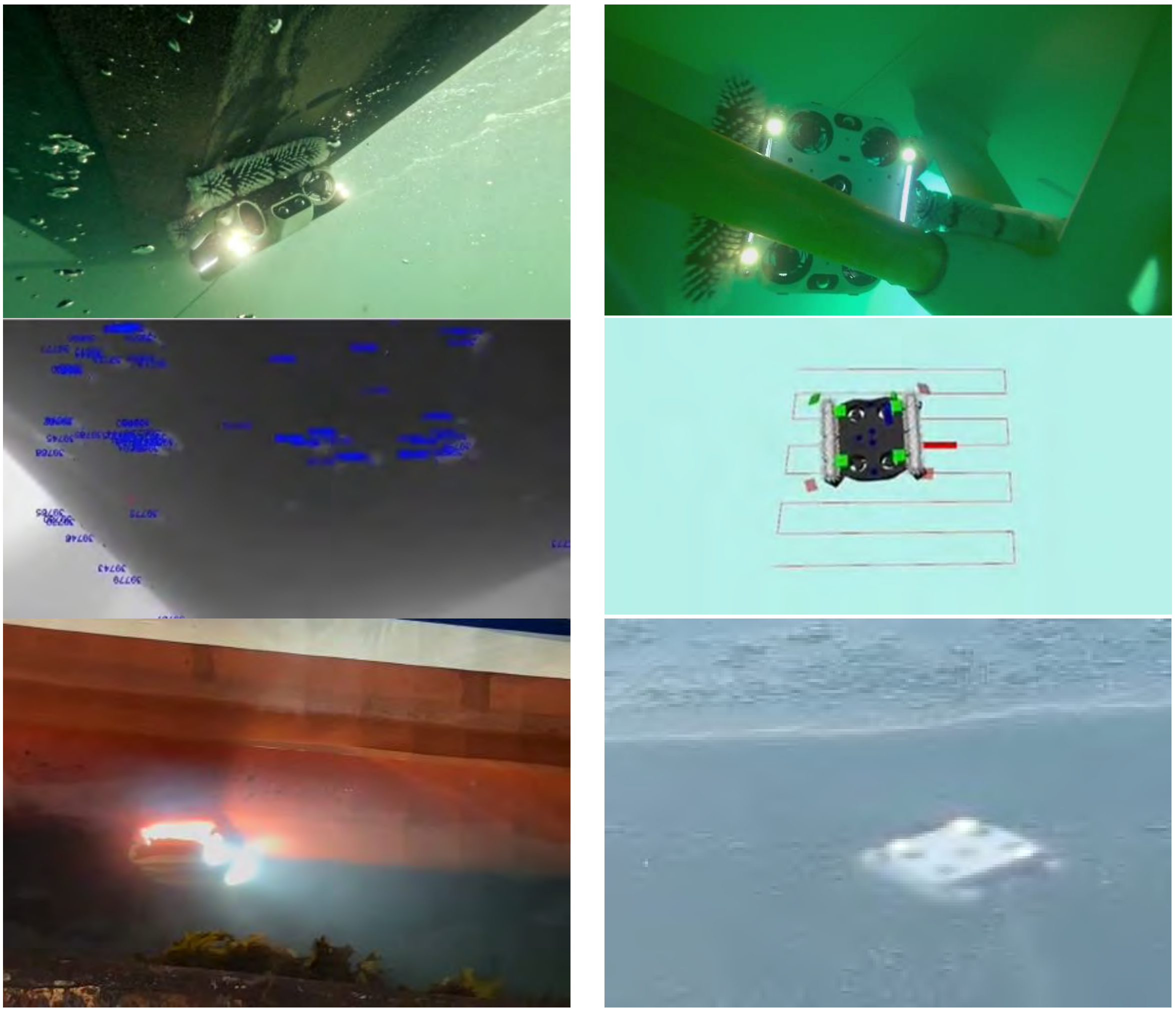

Fig.8: Hullbot's free swimming bot cleaning niche areas in versatile conditions, both in tropical and Alaskan waters under ice. Multiple sensors allow redundancy during fast manoeuvres and snake trajectory to ensure automated full coverage.

4. Opportunities ahead: Stepping away from ineffective siloed solutions towards integrated services for a more sustainable fleet

4.1. Pathways and scalable opportunities for a cleaner sector

Proven robotic in-water cleaning methods, successfully validated on smaller vessels, are now ready for expansion to larger fleets. Recent figures identify potential cleaning windows both at anchorage and in port. As highlighted by *UMAS (2024),* waiting at anchor for a berth represents an untapped efficiency opportunity: industry studies show ships spend 4–6% of their operational year, approximately 15–22 days, at anchor, Fig.9.

In major ports, average waiting times for large container vessels typically range from 44 to 80 hours under normal conditions, with periods exceeding four days during peak congestion in developed countries, *UMAS (2024).* These idle windows present opportunities for regulation-compliant cleaning service deployment.

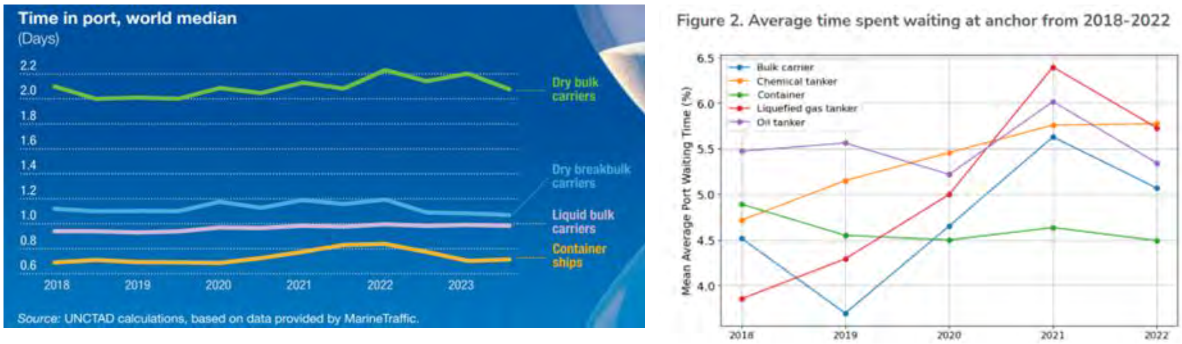

Fig.9: Trends in average global waiting times at anchor and in port, *UNCTAD (2024), UMAS (2024)*

4.2. Feasibility of hull cleaning within port & anchorage timeframes

In-water hull cleaning robots, such as Hullbot's larger system BigBot, can complete comprehensive underwater cleaning of the largest vessels across major commercial categories within typical port and anchorage layover periods. These categories include container ships, dry bulk carriers, tankers, and RoRo/car carriers. To evaluate feasibility, the study averaged representative time-in-port and at-anchorage values obtained from global industry datasets and studies, as well as published peer-reviewed port studies *UNCTAD (2024), SeaVantage (2025), Port+ (2018–2020), BTS (2024), CEIC (2019–2025), UMAS (2024)*, *Ma et al., 2023, Port-Eu (2021,2025)*. The largest vessel in each class was chosen as reference hull surface area estimates, including extra time needed for niche and complex areas.

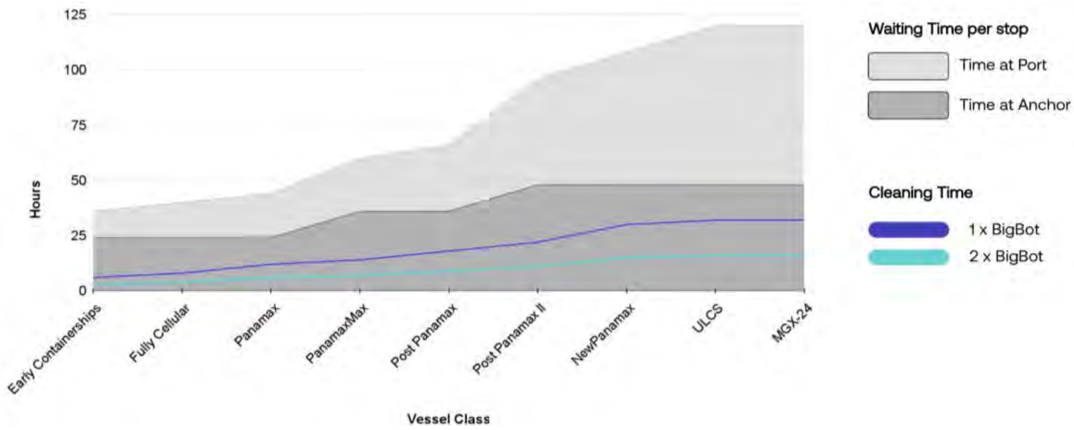

Fig.10: Various container ship types time in port and anchorage in relationship to automated hull cleaning cycles

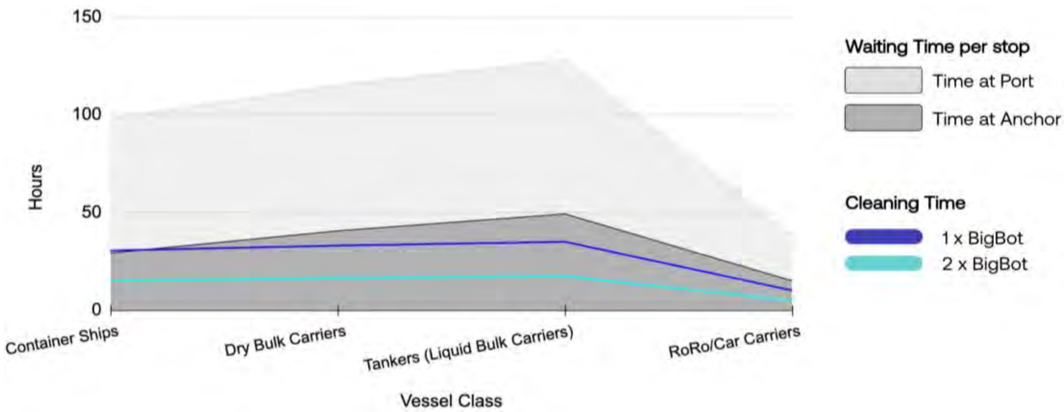

Fig.11: Various vessel types time in port and at anchorage in relationship to automated hull cleaning cycles

Figs.10 and 11 illustrates average typical shipping industry times across varying container ships and four major vessel types. For containerships, the average time was found to be 12 to 72 h per anchor call and 24 to 48 h per port call. For the other five vessel classes, average times ranged from 15 to 50 h per anchor call and 23 to 56 h per port call. Results demonstrate that full underwater cleaning is achievable within typical operational windows when deploying at least one Hullbot BigBot operating at a cleaning rate of 1449 m^2/h, Figs.10 and 11. Cleaning effectiveness and success rates improve further as additional robots are deployed.

4.3. Integration of Hull Cleaning with Vessel Schedules

Building on the demonstrated feasibility of hull cleaning within port and anchorage windows, typical vessel transit schedules across diverse service types create frequent and practical opportunities for routine biofouling management, Fig.12. Transit times across diverse shipping service types, from long-haul to feeder routes, can vary depending on routing, vessel speed, and intermediate port calls; however, prevailing trends reveal consistent patterns that provide sufficient and frequent cleaning opportunities, enabling vessels to comply with biofouling management schedules ideally on a fortnightly basis. This frequency aligns closely with regulatory expectations targeting invasive species control and fuel efficiency improvements. Evaluating biofouling cleaning methods, in transit, at anchorage, or in port, across key factors including execution ease, operational risk, environmental impact, and technological feasibility, indicates that cleaning at anchorage offers the most practical balance. Anchorage cleaning benefits from operational safety, environmental protection, and compatibility with standard vessel waiting times before port entry, *UNCTAD (2023), IMO (2023)*. Thus, the typical frequency and duration of vessel movements shown in the transit time graph support anchorage cleaning as the most viable and effective strategy for routine biofouling management across general shipping routes, aligning with regulatory frameworks and industry best practices to minimize invasive species transfer and optimize fuel efficiency.

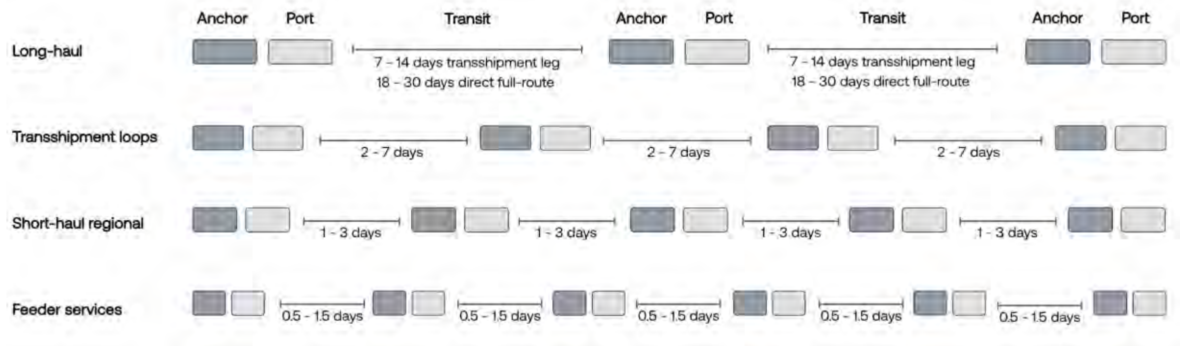

Fig.12: Typical transit times across shipping service types, showing frequent cleaning opportunities

5. Conclusion

All vessel hulls accumulate biofouling over time, including fast-moving, biocide-coated Foul-Release Coatings (FRCs) operating in low-fouling environments, as demonstrated by more than 900 cleaning and inspection operations. Hullbot's gentle, autonomous cleaning robots effectively maintain hull coatings without degradation or environmental pollution, supported by over 3,000 hours of in-field cleaning experience and third-party validations. Maritime operational patterns, specifically cleaning opportunities at anchorage and in port, allow for enablement of frequent and compliant cleaning intervals aligned with shipping schedules.

Moving forward, continued scaling of the deployment of autonomous hull cleaning technology will be essential to integrating routine fouling management into vessel operations and driving decarbonisation of the maritime industry.

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Inferring Barnacle Growth Structure from 2D Imagery Using an Automated Underwater Imaging System with 3D Profilometry-Based Validation

Joshua Anani, Denmark Technical University, Lyngby/Denmark, josan@kt.dtu.dk
Kim Dam-Johansen, Denmark Technical University, Lyngby/Denmark, kdj@kt.dtu.dk
Jochen A.H Dreyer, Denmark Technical University, Lyngby/Denmark, jodre@kt.dtu.dk

Abstract

Traditional biofouling evaluation requires manual and periodic inspection, missing critical growth phases. We developed an automated underwater imaging system for continuous fouling monitoring and biofouling coverage calculation. However, barnacle height could hitherto not be measured from 2D imagery even though it critically affects hydrodynamic drag. Therefore, a machine learning approach was developed to predict height from morphometric features (diameter, area, perimeter) and spatial competition metrics. Neural networks achieved $R^2 = 0.694$, with 68% of predictions within ±25% error. The model excels for barnacles >1 mm diameter (94% within ±25%) but shows reduced accuracy for specimens <0.5 mm (40% error), validated using 3D profilometry.

1. Introduction

Antifouling coatings on ship hulls prevent marine fouling that increases drag, raising fuel and voyage costs, *Cao and Cao (2023)*. Marine fouling evaluation is essential for the development of sustainable coatings and helps optimize hull cleaning while monitoring invasive species, *Hunsucker et al. (2019)*. Traditional evaluation methods rely on periodic manual retrieval and visual inspection of test panels, which presents significant limitations including evaluator bias, macroalgae collapse onto panels during aerial exposure, and missed critical growth phases, *Pedersen et al. (2022)*.

Beyond surface coverage, vertical growth represents a critical parameter for biofouling assessment. Barnacle height directly influences hydrodynamic drag. Studies show that 10% coverage of 5 mm high barnacles causes similar power requirements as 50% coverage of 1.25 mm high barnacles, *Yigit et al. (2017)*. Heavy calcareous fouling can result in 59-86% increases in ship powering requirements, *Schultz (2007), Yigit et al. (2017)*.

The relationship between barnacle morphology and vertical growth is complex. Individual barnacle height correlates with basal dimensions but is modulated by environmental factors including local crowding effects, competitive interactions with neighboring organisms, and resource availability. These spatial relationships suggest that height information may be encoded in the 2D spatial patterns observable from overhead imagery, *Hooper and Eichhorn (2016), Joseph et al. (2023), Munroe and Noda (2009)*.

To address the limitations of manual evaluation, an automated underwater imaging system that enables continuous monitoring of fouling development in natural marine environments was developed. This system captures high-quality images through scheduled acquisition, median stacking for debris and swimming fish removal, and multi-exposure fusion techniques. While effectively tracking surface coverage and temporal dynamics, the system's 2D imagery cannot directly measure vertical growth. Therefore, we present a machine learning approach to infer barnacle height from morphometric and spatial features extracted from 2D imagery, validated against high-resolution 3D profilometry measurements. This integration enables comprehensive 3D fouling assessment using existing automated imaging infrastructure without requiring complex stereoscopic systems.

2. Experimental

2.1. Test Panel Deployment and Barnacle Collection

Acrylic test panels (100 x 200 mm) were deployed at the CoaST Maritime Test Centre (CMTC) in Hundested, Denmark, for two months to allow natural marine colonization. Panels were positioned with one side facing away from the test raft, receiving direct sunlight and promoting mixed algae and barnacle settlement. The panel side with better shade, where the barnacles preferentially settle due to reduced light exposure, provided the primary barnacle populations for this study. This species dominates the local fouling community at the deployment site. A total of 785 barnacles were analyzed across all panels.

2.2. 3D Surface Characterization

Retrieved panels underwent high-resolution 3D profilometry to establish ground truth height measurements. The laser profilometry system (Keyence VR-3000 G2) generated detailed surface reconstructions with ±23.5 µm resolution, producing both spatial maps and height profiles across entire panel surfaces. Maximum height above the panel surface baseline was recorded for each individual barnacle.

2.3. Barnacle Segmentation and Feature Analysis

Individual barnacles were segmented using CellPose with the Segment Anything Model (CP-SAM) to establish precise organism boundaries and prevent erroneous fusion of adjacent specimens, *Pachitariu and Stringer (2022).* Following segmentation, comprehensive features were extracted spanning three categories: morphometric dimensions (diameter, area, perimeter), shape descriptors (circularity, form factor), and spatial competition metrics (nearest neighbor distance, competitive size advantage). Log-transformed features captured the non-linear scaling relationships characteristic of biological growth.

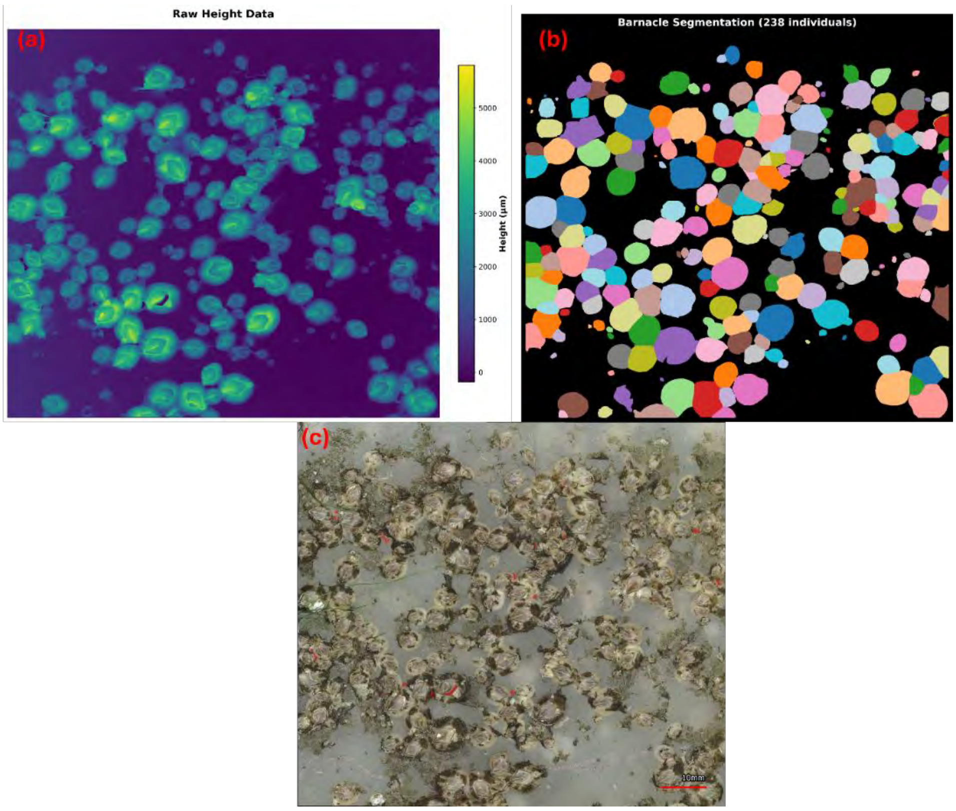

Fig.1: (a) Test panel with barnacle colonization extracted from height profile of the 3D profilometer; (b) CP-SAM segmentation showing individual boundaries (c) barnacle images from 3D profilometer (red patches are areas where the profilometer failed to resolve)

2.4. Machine Learning Development

A neural network model was developed with architecture of 12 input features feeding through hidden layers of 32 and 16 neurons to predict barnacle height. The model incorporated 40% dropout regularization to prevent overfitting. Training employed 80% of the data (628 barnacles) with 20% (157 barnacles) held as a completely unseen validation set, stratified by height distribution to ensure representative sampling. Fig.1 shows the height map of the barnacles, the segmented individual barnacles and their corresponding unprocessed image.

3. Results & Discussion

3.1. Overall Model Performance

The neural network successfully learned the complex relationships between 2D morphometric features and barnacle height, achieving an R^2 of 0.694 on the unseen validation set compared to 0.714 on training data. This minimal performance gap demonstrates robust generalization without overfitting. The mean absolute error of 520 µm on validation data closely matched the 516 µm training error, with 68.2% of predictions falling within ±25% of measured heights, and 77.7% falling within ±30%.

3.2. Size-Dependent Performance Patterns

Model accuracy showed dramatic improvement with increasing barnacle size. Large barnacles exceeding 1.5 mm diameter achieved exceptional performance with 94% of predictions within ±25% error and mean errors of only 12%. In contrast, tiny barnacles below 0.5 mm diameter proved challenging, with mean errors of 40% and fewer than half achieving the ±25% accuracy threshold. Fig.2 shows the measured vs predicted accuracy of the model for the 157 barnacles used for the validation process.

This size-dependent pattern reflects both technical and biological factors. At sub-millimeter scales, the 3D profilometry approaches its resolution limits while young barnacles exhibit more variable growth patterns that may not yet conform to mature allometric relationships, *Doell et al. (2017).* The strong negative correlation between barnacle size and prediction error ($r = -0.402$, $p < 0.001$) confirms that measurement uncertainty and biological variability compound at smaller scales.

3.3. Spatial Competition and Ecological Effects

Beyond simple size effects, the analysis revealed that spatial competition profoundly influences prediction accuracy. Barnacles much smaller than their neighbors exhibited 49.5% mean error—nearly triple that of barnacles with competitive size advantages (16.4% error). Similarly, barnacles in very dense conditions showed substantially higher errors than those in sparse conditions.

These patterns suggest that competitive stress disrupts normal allometric scaling. Typically, under crowded conditions barnacles grow in height faster and have slimmer and longer shells than their conspecifics from sparsely populated areas, *Varfolomeeva et al. (2008).* Small barnacles surrounded by larger already established neighbors likely experience resource limitation through reduced access to water flow and food particles. This ecological pressure manifests as stunted or irregular growth that deviates from the power-law relationships captured by the model's log-transformed features.

3.4. Feature Importance and Biological Validation

The model's reliance on perimeter-based features as primary predictors aligns with biological expectations, as the perimeter represents the actual tissue attachment boundary governing nutrient uptake and growth potential. The prevalence of log-transformed features among the top predictors confirms that barnacle growth follows power-law rather than linear scaling—a hallmark of metabolic scaling theory in marine organisms.

Spatial competition metrics comprised 25% of the model features, quantifying for the first time how local ecological interactions influence individual morphology in barnacle communities. The spacing-to-size ratio and competitive size advantage features capture the reality that barnacle growth depends not just on individual potential but on the competitive landscape.

3.5. Model Performance Analysis and Future Improvements

For established barnacle communities where individuals exceed 1 mm diameter, the model provides reliable height estimates with median errors around 17%. This demonstrates the feasibility of inferring 3D structure from 2D imagery using existing underwater monitoring systems.

The primary challenge involves tiny barnacles (<0.5 mm), particularly those in competitively disadvantaged positions surrounded by larger neighbors. These small, crowded specimens experience both measurement limitations and biological stress that disrupts normal growth patterns. The combination of small size and competitive suppression—where tiny barnacles are overshadowed by larger neighbors—creates the most challenging prediction scenarios with errors exceeding 40%.

These limitations largely reflect insufficient training data rather than fundamental methodological constraints. The validation set contained only 23 tiny barnacles, and even fewer in extreme competitive situations. With expanded datasets targeting early-stage fouling and high-density mixed-size communities, the model could learn the modified growth patterns that occur under these challenging conditions. Future work should focus on systematic collection of small barnacle data and confidence scoring based on size and competitive environment to identify predictions requiring verification.

Importantly, while the model shows reduced accuracy for tiny barnacles, larger barnacles (>1 mm) that contribute most significantly to hydrodynamic drag are predicted with high reliability (94% within ±25% error). This performance threshold makes the model particularly suitable for operational deployment, where it can be integrated with underwater camera systems to provide continuous 3D fouling assessment and inform optimal maintenance schedules for antifouling coatings based on actual barnacle height distributions rather than simple coverage metrics. However, field validation remains essential—the model must be tested in real marine environments with mixed fouling communities and predictions periodically validated against 3D profilometry to ensure accuracy across diverse ecological conditions and coating types.

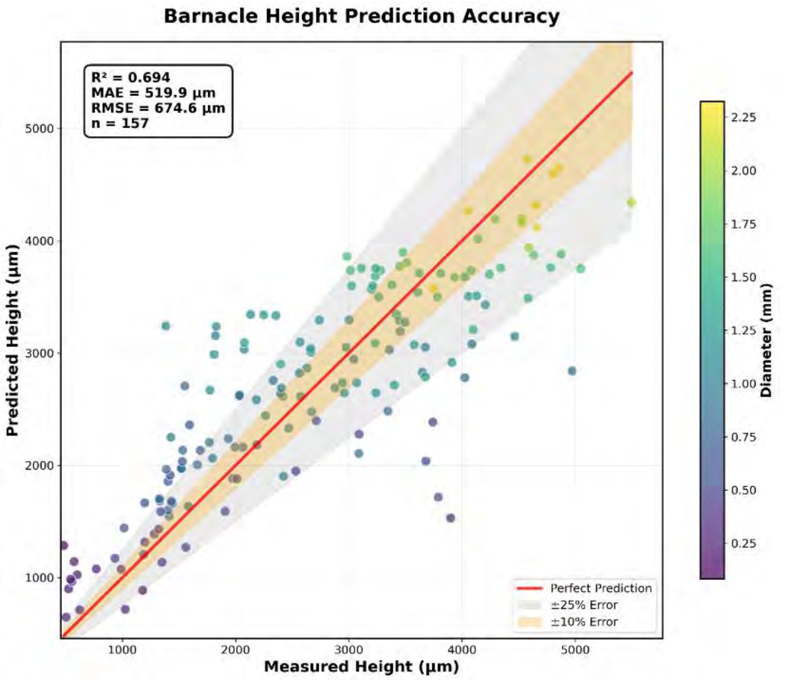

Fig.2: Scatterplot showing size-dependent prediction accuracy with confidence bands

4. Conclusion

This study demonstrates the feasibility of predicting barnacle height from 2D morphometric features using machine learning, achieving 68% accuracy within ±25% error. The neural network model successfully integrated basal dimensions, shape descriptors, and spatial competition metrics to infer vertical growth patterns, enabling comprehensive 3D fouling assessment without expensive stereoscopic hardware.

The approach excels for mature barnacles (>1 mm) while tiny specimens in competitive environments remain challenging. Small barnacle growth in competitive environments proved unpredictable, suggesting complex biological interactions that deviate from standard allometric patterns. Expanding the dataset with more early-stage and high-density samples could potentially help the model learn these challenging growth patterns, though the inherent variability in competitively stressed organisms may impose fundamental limits on prediction accuracy.

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Lessons in Advanced Hull Cleaning

Karl Lander, Subsea Global Solutions, Miami/USA, karl.lander@sgsdiving.com

Abstract

This paper presents a series of lessons learned from the advancement of a variety of hull cleaning technologies to meet emerging global requirements. Topics addressed include adoption of robotic technologies by a traditionally diver-centric organization, introduction of capture and treatment technologies for nice area cleaning and propellor polishing, and challenges with completing testing requirements (both for cleaning and filtration/treatment). Included are lessons learned from both the commercialization of technologies and an ongoing (at time of writing) demonstration event with Transport Canada.

1. Introduction

Hull cleaning is not new by any stretch but has only advanced incrementally through the centuries. Recent increased demand for cleanings, coupled with tighter regulations around cleaning, is driving unprecedented advancement in the market. Much of the advancement in technology is coming from new entrants into the field, ultimately driving a more competitive market forward. Despite being positioned as a traditional global leader in underwater ship repair and maintenance, Subsea Global Solutions is driving advancements in environmentally friendly hull cleaning, as well as adapting to customer expectations for robotic solutions. The need for divers for subsea maintenance will remain for many years, however the prudent organizations will learn to how to maximize the unique skillsets divers bring through adoption of other technologies where appropriate.

2. Emerging Requirements and Expectations

New regulatory guidance and industry best practices from various factions around the world are influencing the direction of hull cleaning, both in terms of how it is performed, and how frequently it is performed. Countries such as New Zealand, Brazil and Norway are stipulating that ships entering their waters must be free of macrofouling, and the case of the latter two, also mandating that cleaning of macrofouling must be performed with systems capable of capturing dislodged material and treating or filtering the waste. These requirements are merely the logical follow-on from the previously published biofouling guidance from the International Maritime Organization (IMO) and will serve to guide the IMO's development of a mandatory instrument in the coming years. The impacts of the regulations on service providers are pretty obvious, and many service providers are well out in front of the guidance through their various solutions, including proactive (hull grooming) robots, and advanced capture and filtration technologies. This is not news.

However, Subsea Global Solutions has observed that there is a perception from shipowners that only the new players in the market are capable of meeting the new requirements, and that robotic solutions are automatically perceived as superior to diver provided solutions. Increased expectations for safety, convenience, cost, regulatory approval, quality of the cleaning, and impact to the coating system are all understandable. And a healthy market should demand such improvements. But it also does not mean that robotic solutions are the exclusive solution or that diver involved solutions have no place in the market. Customers and providers must understand the value propositions and tradeoffs of each type of solution and choose the best solution for the task at hand.

3. Adoption of Robotic Technologies

There are several valid reasons, in general, to adopt robotic technologies over human operated ones. The most compelling are cost and safety, with quality and efficiency next on the list. Good, fast, cheap, safe. Everything after that is some further specification of one of those factors. In some locales, we have seen safety concerns drive regulations that then in turn influence service providers. For example, Singapore mandates 5 or 7-person dive teams and only permits dive operations during daylight hours, and diving is prohibited during cargo or bunkering operations. Robotic operations do not have the same manpower mandates, nor do they have the same level of restrictions regarding daylight or concurrent operations. A safety regulation created an efficiency and convenience value proposition for the use of robotic solutions, and providers would be foolish not to leverage technology if they wish to remain competitive in a given market.

As mentioned in the prior section, customers have increased expectations around the use of new technologies, and if a given provider does not have the technology the customer may look for someone else who does have it. In this case, it is crucial to understand the "why"; why does the customer want that new technology?

When it comes to ship inspections and maintenance, there are many things that a diver "can" do that an ROV cannot. Divers can touch things, manipulate tools, compare things, answer questions in real time. ROVs are still developing many of those capabilities. Because of this, it easy for a dive company to believe that a diver is better than an ROV. And if a diver is better, why would a dive service provider want to use an ROV to provide a lesser product? Why indeed?

In the case of inspection, an ROV provides the customer with a lower cost, safer, possibly more efficient inspection that is "good enough." True, the ROV might discover an issue that requires diver intervention, whereas a diver could have resolved it on the spot. But the customer is making the decision that the likelihood of that is low enough to choose the ROV as the most cost-effective way to gain the information needed. Divers are a premium commodity and it is crucial for both providers and customers to understand that.

Fig.1: C-ROV underside with nylon brushes

Considering these factors, Subsea Global Solutions is integrating robotic inspection and cleaning technologies into the product portfolio. Inspection ROVs are available at a couple of the service locations, and the internally developed Cleaning ROV (C-ROV) is being gradually rolled out across the company. The C-ROV is a brush-based cleaning solution, that can be easily adapted to meet the range of cleaning requirements, from non-contact hull grooming, up through aggressive barnacle busting, and can integrate with a capture and filtration system. The C-ROV itself occupies a fairly small footprint and is easily transportable and deployable, allowing significant operational flexibility, enabling customers to receive cleaning services in locations where options may traditionally have been limited. This includes forward staging of the system onboard a vessel and having a small cleaning crew travel to meet the vessel as needed. A combination approach of using the C-ROV to clean the vertical sides and flat bottom, while divers address the niche areas has proven to be a cost effective and efficient approach. Further, this hybrid approach has helped alleviate concerns from divers who may be concerned about robots taking their jobs. They can see firsthand the capabilities and limitations of the system, and better understand how to differentiate themselves as skilled subsea technicians, and also come to appreciate not having to perform the less desirable work of vertical side or flat bottom cleaning.

4. Capture, Filtration and Treatment

As previously noted, more locales are choosing to require capture and treatment of removed macrofouling, and additionally a few are also requiring treatment to minimize the release of biocides into the local waters. Subsea Global Solutions has been working for a number of years on technology to address the issue of biocides in the water, in addition to dealing with the solid material removed. The first piece of the puzzle is effective capture of material at the hull of the ship. Two cleaning tools are possible options. The C-ROV can be outfitted with shrouding and a suction uptake, Fig.2. A second larger system, the Remora, Fig.3, can also be used when capture is required. Unlike the C-ROV, the Remora is a diver operated system. While larger and slightly faster than the C-ROV, it is logistically more challenging to operate. Management of the diver's umbilical in addition to the Remora's umbilical and capture hose creates a layer of complexity not present with the C-ROV system.


Fig.2: C-ROV equipped for capture


Fig.3: Remora

To address the issue of the captured material, to include the biocides in the water, the WhaleShark filtration system was developed. The WhaleShark consists of a coagulant tank, flocculent tank, settling tank with a clarifier and a multi-stage filtration system that filters particulate matter down to 1 µm. Water is pumped from the cleaning unit into a rotating drum filter to remove the larger particulate matter. The influent is then dumped into the dosing (coagulant and flocculent) tanks for the addition of chemicals. Water then flows into the settling tank to allow biomass and paint debris to precipitate out of solution and settle in the bottom of the tank.

Soluble metals (copper and zinc) are coagulated out of solution and bound together by the flocculent so that they may also settle in the bottom of the settling tank. Water then passes by the clarifier and is pumped into the next stage of mechanical filtration down to 5 µm. and then down to 1 µm. The water is then pumped into Organoclay tanks where the treated / filtered influent is polished prior to release as effluent to the environment. All solid waste is collected and disposed of by a certified solid waste disposal company that maintains chain-of-custody documentation as the waste is disposed of in a regulatory compliant fashion.

Subsea Global Solutions also uses a purely mechanical filtration system in several locations that does not address the issue of biocides, and may incorporate ultraviolet light treatment of the effluent to address any remaining organisms that pass through the final 1 μm filter.

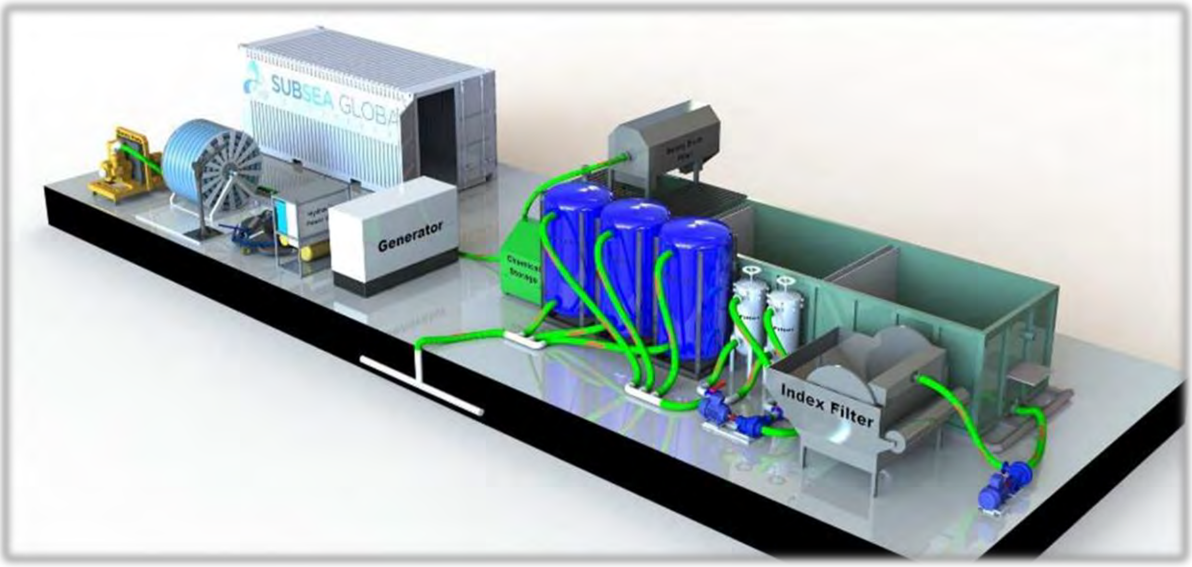

Fig.4: WhaleShark filtration and treatment system

Fig.4 shows the layout of the complete system comprising the Remora, the WhaleShark and a dedicated generator to power the system. Testing to date has proven that the WhaleShark can remove a significant amount of the dissolved metals from the influent, but it requires a significant footprint and is not easily transportable.

5. Testing, Certification and Standards

Subsea Global Solutions occupies a unique space in the cleaning market due to our large global footprint, with 14 offices in 8 countries. This translates to 8 sets of national guidelines, 14 sets of local guidelines and numerous other sets of guidelines for all the other nearby ports that we operate in. It is well known that no uniform standard for testing or compliance currently exists, although recent efforts such as the development of ISO 20679 will be extremely helpful if and when local authorities opt to accept those prescribed test procedures. Requiring individual tests and demonstrations for each port will slow the uptake of new technologies across the industry and may run counter to the long-term goal of ensuring clean ships are sailing the oceans.

Necessary tests and acceptable thresholds remain issues to be addressed, both at the global and local scales. Subsea Global Solutions has been participating in a demonstration event with Transport Canada on in-water hull cleaning and intended to conduct tests of the water samples to local for the presence of microplastics and nanoplastics released from the coating, with testing to be performed in accordance with ISO/DIS 24187 and/or ASTM D83302-20. This would be extremely valuable information; however, at writing, no laboratory had yet been identified that could perform the tests in an economically viable manner.

During different testing of the WhaleShark in a US port, the issue of the lack of policy specific to in-water hull cleaning was discovered. The effluent from the WhaleShark was being treated as industrial discharge from a point source. What the local regulation lacked, however, was the ability to recognize that the source water was the harbor itself, and that the effluent was sufficiently lower in copper content than the ambient harbor water, to the degree that the WhaleShark was effectively cleaning the harbor. However, since Whaleshark was being viewed as a point source, its discharge was considered additive to the harbor and subject to the Waste Load Allocation and thus a permit could not be issued.

6. Summary

With the requirements for ships to have hulls free of macrofouling sail from port to port only increasing, the demand for hull cleaning and hull inspections is only going to increase, and it is critical that all stakeholders move forward in a coordinated effort. This paper has laid out some of the challenges that exist to advancing the industry, particularly on the regulatory front as it is related to permissions to perform cleaning activities. Uniform standards and expectations will go a long way to ensuring shipowners have access to the services they need and that service providers have a clearly defined playing field on which to compete.

Acknowledgement

Many thanks to the regulatory bodies around the world who have been supportive of these emerging technologies and are looking for ways to ensure that hull cleaning can occur in environmentally friendly ways to keep our oceans and planet healthy. These organizations include, but are not limited to Transport Canada, California State Lands Commission, California Water Board, The Rikswaterstaat and the Flemish Ports.

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Experience with In-Transit Cleaning of Hulls

Rune Freyer, Shipshave, Stavanger/Norway, rune.freyer@shipshave.no
Masaki Katafuchi, Shipshave, Stavanger/Norway

Abstract

This paper discusses some key issues of in-transit cleaning, based on the experience gained with the ITCH (In Transit Cleaning of Hulls) system. The paper gives answers to questions such as: What is the experience with ITCH and paints? How can we evaluate the effects of the cleaning and when is ITCH a viable alternative? How can information capture from in-transit cleaning be used for better repainting information? When will it be environmentally sound against invasive species?

1. Introduction

Hull grooming is employed increasingly, but extensively as a proactive maintenance strategy to reduce hull resistance and maintain vessel efficiency. In-transit grooming is used by many ship operators, where the hull is cleaned while the vessel is underway. The primary motivations for this method include gentle interaction with the paint, continuous cleaning without disrupting transport schedules, eliminating reliance on third-party suppliers, and preparing documentation for port authorities. With shipping entering fuel efficiency penalties, there may not be room for vessels that are not proactively cleaned in the future unless a perfect antifouling is developed.

In-transit hull cleaning opens new challenges and opportunities. The operations are performed outside ports and territorial waters. Being operated by the crews, it requires other thinking than a third-party service purchase. Open seas and speed with daytime operations ensures clearer visibility than in port. The fact that all cleaned surfaces are recorded before and after cleaning also poses opportunities.

The introduction of roughness measurement of paint and fouling is also a quantitative way to assess paint damage and state of fouling.

Traditionally, hull efficiency has been estimated using indirect methods such as fuel efficiency analysis, video documentation of cleaning operations or inspections with remotely operated vehicles. However, these approaches often suffer from limitations, including low measurement accuracy, inconsistent data collection, insufficient sample sizes for robust statistical analysis, and high operational costs. In contrast, modern industrial processes routinely utilize high-precision measurements and large datasets to optimize performance. Given its significant impact on fuel consumption and environmental performance, hull roughness deserves similarly advanced measurement methodologies.

Videos of the flow along the hull in transit is now a routine activity performed by many crews. A new system that measures hull roughness while simultaneously recording videos and performing grooming is now in its semi-commercial stage.

SPCs and FRCs have different effluent problems, and both will be scrutinized in the future. Some ship owners optimize paint selection on location of the hull, mainly because of paint cost. Optimizing different areas of the hulls can be possible with insight from big data and roughness sensors.

2. The use and analysis of in-transit hull cleaning

In-transit hull cleaning was introduced in 2020 for cleaning hulls while operating at ship speeds between 10 and 14 knots. The aim is to always keep a clean hull rather than to wait for degrading hull performance. The tools are carried by the ship and operated by the crews. As ITCH is operated offshore, it does not require port permits. A cleaning operation can be performed within hours, depending on ship size and fouling level. The system was first intended for slime, but further R&D has allowed removal of heavier fouling as well, including barnacles. The fuel efficiency benefits were exemplified in a study by DNV on two large container vessels showing fuel savings of 5% and 16%, *Hollenbach (2024)*. The system today is used on container, bulk and tank vessels from 128 to 400 m length and with fouling release and self-polishing paints.

A survey conducted at HullPIC 2019, *Schmode et al. (2019),* established that inadequate measurement and analysis was the biggest challenge in hull performance. The ITCH system has been independently proven with indirect analysis methods (traditional fuel efficiency derived analysis), but the analysis can be expensive. Gaining confidence in quality analysis can take years from the first cleaning till the analysis is ready. With FuelEU efficiency penalties being introduced, *EU (2023),* and others in the pipeline, the industry hardly has the time to wait.

Qualitative evaluation is done by watching fouling removal videos that is captured during cleaning operations. At daytime offshore, the water is clear and video quality good. The fouling plumes are immediately carried away and do not obstruct the view. The video can be combined with areal coverage plots to get a good impression over cleaning.

The videos are also unique in capturing flow events on the hull. The path of the bubbles in air lubrication systems is important for the fuel savings but is difficult to simulate. But bubble streams that exit from the flat bottoms will show on the sides of the hull.

3. Cleanliness, paint damage and fuel savings

The ITCH system was designed to keep a functional antifouling paint clean through preventive cleaning with precise numbers of strokes and controlled load on brush fibers. The aim is to clean without damage to antifouling. This has been verified in the lab and with third-party inspections in dry-docks after use. After further technology development, experience has shown that the ITCH can also remove established fouling, proving savings even by cleaning ships 4.5 years into the dry-dock cycle. Hulls previously cleaned by ROV or divers are difficult to clean because of the damage to the surface.

Barnacles stick to the hull and much force is required with brushes. Sharp barnacle fragments in a rotating brush can cause secondary antifouling damage as severe as the primary damage. The ITCH system crushes the barnacles without scratching the antifouling and the debris is immediately carried away.

An example of fuel savings is given in the Hapag Lloyd/DNV study showing 5% and 16% reductions. However good these hulls were maintained, these savings show that unnecessary losses of 5% and 16% had already happened. A preventative grooming plan will avoid this altogether.

4. Invasive species

Organisms found on hulls require surfaces to adhere to and spread on coastlines. Organisms in ballast water are planktonic or have swimming capability and thrive free floating in an ocean. The spores from fouling will generally adhere to surfaces or sink. In-transit cleaning is performed outside territorial waters in deep seas. Most spores will therefore sink to the bottom below the depth of photosynthesis without creating viable communities. Like all other hull cleaning systems, ITCH cannot cover all the areas and supplementary cleaning of niches, foremost on the bow, aft, bilge keel and flat bottom may be needed against fouling.

5. Paint damage

Ship owners and paint companies are reluctant to use traditional cleaning because it damages and reduces the efficiency of the antifouling. Laboratory tests confirmed no thickness loss due to paint damage with ITCH. However, ship owners want their own verification in real life. Paint damage was therefore an evaluation criterion for ITCH for many pilots. Evidence of paint damage has not been seen after numerous dry-dock inspections. The ITCH has controlled surface pressure, thin bristles and controlled numbers of strokes and this reduces paint damage compared to more aggressive methods.

6. Piloting in-transit cleaning

Ship owners only rely on their own experience and small-scale piloting is therefore required before an owner implements widely. Frequently, fuel efficiency estimates are required despite the inaccuracies and the work and delays involved. Fuel efficiency estimates have low resolution and random events are likely to affect the results. Statistical confidence needs a population of more than one vessel to predict success. Other fuel efficiency tools like air lubrication or sails require million-dollar investments while ITCH needs less than $1/10^{th}$ of that. The more successful pilot projects have 4-5 installations. This produces more information and higher confidence.

Crew reactions vary between "ITCH cleaning is the most motivating work on board the ship" to captains saying "we don't have manpower available". Shore management needs to ensure that progress is made.

A good piloting strategy involves 4-5 installations, has a plan for quantifying the value of the ITCH, has concrete success criteria, a commercial implementation strategy if milestones are reached and a responsible engineer. The implementation strategy should be action oriented with "IF-THEN" approach. These pilot projects are normally profitable by themselves due to fuel savings.

7. Organizing in-transit hull cleaning

In-transit cleaning eliminates interfaces with third-party suppliers, reducing workload for the Performance Engineer and buyers. However, hull cleaning is an added operation for the crew. Crews need to be motivated, instructed and trained to make sure the systems are used. Onshore coordination and follow up is needed to make sure continuous use. Because the operation is performed during transit, the crews can find a time that fits.

Traditional hull cleaning	**In transit hull cleaning**
Data harvest	
Analysis of fuel performance	Auto scheduled in PMS ±2 months
Decision making on cleaning ±1 year	Organize 2 crew members to clean
Schedule service provider with ship arrival	Evaluate videos, and inspect tool for spares
Permit for cleaning in port	
Arrangements with rescheduling of supplier	
Deferral of ship schedule to allow idling	
Receive report and evaluate results	

Data is generated anytime the ITCH is in the water. An obvious way to use the data is to analyze the cleaning operation and possible improvements. Areal coverage, cleaning efficiency and a traditional visual video inspection. Any afterwork is now made more efficient with new software to navigate videos and report automatically.

Roughness measurement allows detailed understanding of paint quality and antifouling properties of the paint. This can create time series of antifouling evaluation over the hull, over the fleet and over specific areas of the hull. A semi-commercial version is available today and has been used on a number of vessels.

ITCH videos are unique in filming the hull while sailing. This allows other verification such as benchmarking CFD or showing if air lubrication escapes along the vertical bottom.

8. Technical working window

The working window of ITCH commercially proven is vessels from 128 m to 400 m overall length with laden draft of 6 m to 21 m. Operating speed of 10-14 kn, but has also been successfully operated at 9-18 kn. Some applications on ferries and cruise ships are somewhat limited by stabilizer fins. The main limitation is cleaning of ships with dysfunctional antifouling, i.e. paint damages from previous ROV/diver cleaning.

9. Vision for further development

The focus of developments is on basic functionality, i.e., user interface, reliability and efficiency. The other direction is making hard facts for hull surface management enabling unique fact-based hull performance decisions.

10. Obstacles for decarbonization

No value chain with carbon neutral fuel can cover the entire needs of shipping for 2050. Less sexy fuel efficiency measures are needed independent of fuel type. Sails, air lubrication, sonic propeller antifouling, boss caps, advanced rudders and grooming still have a hard time to reach fleet implementation. Mainly weather routing and hull cleaning, including ITCH, are the measures that can be utilized without dry dock. With 5-year docking cycles, most of those solutions are not applicable in the near term for many ships.

In pilots, ship owners require inaccurate fuel efficiency numbers to generate indisputable evidence of technologies with pilots in one vessel. Statistically this is impossible. For progress it is implausible. Innovators need to grow market penetration and organizational excellence to enhance the technology. When new technologies show real value and short payback times, more forceful implementation by ship owners will enable innovation in shipping.

Between paint manufacturers there is a reluctance to recommend hull cleaning, but through lab testing and dry-dock inspections, paint manufacturers have become gradually more aware of the distinction between grooming and cleaning and the significant difference in paint degradation. This is still in development.

11. Conclusions

This paper has presented learnings from the use of ITCH cleaning through the last 5 years and thousands of cleaning runs.

Paints are large investments, are expected to last for 5 years but the decision process has too little quantitative information. The paper mentions a semi-commercial roughness measurement to better design painting and define a value on the performance.

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Informing Ports: Biocide & Antifoul Paint Particle Release During In-Water Cleaning, & Impacts on Marine Invertebrates

Anna Yunnie, PML Applications, Plymouth/UK, anyu@pml.ac.uk

Abstract

Environmental concerns over the combined impacts of antifoul coatings (AFC) and in-water cleaning (IWC) have restricted the uptake of IWC practices globally. Fears of sediment contamination from coatings is one of the major drivers for this restriction, but evidence to test the validity of this concern is lacking. PML Applications carried out testing on behalf of the UK Ministry of Defence (MOD) to establish the potential environmental impacts of cleaning AFCs on selected marine invertebrates known to live in the Tamar Estuary, UK. This estuary houses Europe's second largest naval base and is also a highly protected marine area. Results were wide ranging and clearly demonstrated the importance of compatibility between coatings and cleaning systems and the use of high-quality coatings. This paper publicly presents some of these results for the first time and illustrates the need for independent testing of coating and cleaning system compatibility so that Ports and vessel operators can make informed decisions.

1. Background

Following a multi-year, multistage selection process on behalf of the MOD to select the best performing AFCs for their various and unique operational profiles, the final stage of testing investigated the compatibility of each coating with various IWC methods to determine environmental impacts of this activity on the surrounding waters and marine organisms. The aim of the work was to provide the local Port Authority with the data required to make an informed decision on a permissions enquiry for in-water cleaning within their area of jurisdiction.

Specifically, the work was designed to answer a set of questions; a subset of these questions are presented in this paper:

- Is in-water cleaning of antifouling coatings likely to cause marine pollution?
- If so, what types or format of pollution could be expected?
- How much pollution could be expected to occur from one cleaning event?

Previously published studies have provided answers to certain questions but were all limited to specific coating and cleaning types. Additionally, pre-trial literature reviews indicated that no information could be found that investigated the direct environmental impacts of the combined products released during the cleaning event, i.e. paint particles and biocides acting in synchrony. This work aimed to produce data that investigated multiple coatings and cleaning methods by firstly quantifying the levels of biocide and particle release from cleaning and secondly categorising and quantifying their impacts on local benthic organisms.

2. Tests & Methods

Using the novel and bespoke small-scale cleaning techniques described in PML Applications PortPIC paper and presentation, 2024, selected coatings underwent an IWC trial designed to answer the questions posed. This system is based around a scaled down cleaning system which uses a single cleaning head rather than the entire multi-head device. The cleaning head is held and controlled in a bespoke rig, and cleaning trials are carried out in a test tank.

3. Test Panels and Cleaning Methods

- Coatings: Four test coatings were used in the trial:

  - Biocidal self-polishing co-polymer (SPC) coating,
  - Hybrid non-biocidal SPC coating,
  - Hybrid biocidal foul release (FR) coating,
  - Non-biocidal FR coating.

- Additionally, an epoxy primer was used as a negative control, and copper panels were used as positive controls, along with a lower quality, commercially available, biocidal SPC for comparison.

- Cleaning Methods: three types of commercially available IWC methods were used in the trial, all as a single cleaning head unit:
  - Soft polyester bristle brush attached to standard hand cleaning tool,
  - Medium polyester bristle brush attached to a standard hand cleaning tool,
  - A single cleaning head from a commercially available high pressure water jet IWC system configured to optimal settings in accordance with the manufacturer

Optimal settings for each cleaning method on each coating were determined through consultation with IWC professionals and during pre-trial tests conducted on extra panels.

4. Sampling

Measurements were taken prior to and after each cleaning event detailing dry film thickness (DFT), surface roughness, level of fouling (LoF), and damage to coating. Water samples were taken following each clean and tested for the following:

1. Metals analysis: tin, zinc and copper were measured using Inductively Coupled Plasma Mass Spectrometry (ICP-MS).
2. Microalgal ecotoxicology: a short, ten-day bio-assay growth test was used to directly test the relative toxicity of any dissolved and particulate pollutants found in the water generated during each cleaning event. Chlorophyll fluorescence data were used as an indicator of both growth and health of algal cells, with growth rates compared to control samples.
3. Antifoul paint particle characterisation and release rates: paint particles were collected after each cleaning event by filtering effluent water through a 1 µm polycarbonate filter. These were analysed using high resolution macrophotography and image analysis software with colour thresholding. Particle number, size and the equivalent circular diameter (ECD) were calculated; from this the particle counts and the area of coating lost per square meter of coating area cleaned could be extrapolated.
4. Benthic organism ecotoxicology: robust ragworms (Hediste diversicolor) and comparatively less tolerant cockles (Cerastoderma edule) were exposed to representative paint particles at different concentrations to quantify the impacts of toxins contained in the test coatings. The experiment was divided into two sections, with each section carried out under five different APP concentration levels, plus controls:
   - Eight-day, short-term exposure experiment to calculate lethal concentrations of APP (calculated as the lethal concentration for 50% of organisms in each group, or LC50).
   - A twenty-eight-day, long-term exposure experiment to investigate sub-lethal health effects such as weight change, feeding rates and also behavioural changes such as burrowing and sensitivity to touch.

5. Results

A limited set of results are presented here, in answer to some of the questions posed by the Port Authority. Full results will be given in the forthcoming peer reviewed paper.

5.1. Is in-water cleaning of antifouling coatings likely to cause marine pollution?

Based on the results generated for this work, any form of reactive in-water cleaning of antifouling coatings without capture (or "open-circuit") has the potential to result in some form of marine pollution into the marine environment. However, the amount of release resulting from cleaning compatible, high-performance AFCs with appropriate reactive IWC systems could be comparable to, or less than, the release of pollution generated by a vessel coated with an effective biocidal SPC when simply moored alongside for 24 hours.

The amount and type of pollution varies considerably as a result of coating type and cleaning method. The high-performance coatings used in this trial show significantly lower levels of pollutant release than the lower performance biocidal SPC control coating tested for comparison, in terms of both biocidal and APP release.

It is crucially important to note that any ship coated in an effective biocidal AFC is likely to release some level of biocide and paint particles from the coating during static periods, commonly described as "passive release". Equivalent levels of biocide released during the simulated cleaning event of the test biocidal SPC coating was calculated to be less than levels predicted to be released during one single day of passive release from a UK naval frigate, for all three cleaning methods. In fact, it was calculated that nearly two full vessel cleaning events could take place before the equivalent amount of copper would be released passively in a single day.

If reactive cleaning systems with effective capture (or "closed-circuit") and effective filtration units are used, this pollution could be decreased even further. Any cleaning of developed macrofouling assemblages also has the added benefit of halting the typically daily release of gametes and larvae from reproductive organisms within the biofouling assemblage. The use of proactive cleaning regimes, utilising frequent, gentle cleaning, should again reduce pollution concerns.

5.2. If so, what type/format of pollution could be expected?

The type and format of marine pollution is highly dependent on the coating type, for example:

Non-biocidal coatings: In these trials, the total particle area released from the non-biocidal FR coating was minimal with all three cleaning methods; with the exception of cleans with the medium brush. The effects of paint particles for both non-biocidal ACFs on marine organisms in this trial were found to be negligible, and in many cases indistinguishable from "normal" background levels. However, this experiment only looked at short term impacts; long term effects are yet to be fully investigated.

Biocidal coatings: In these trials, the total particle area released from the test biocidal SPC coating was minimal with all three cleaning methods. The biocidal FR coating performed well using the HP jet and soft brush cleaning methods but released significant amounts of copper using the medium brush, which concurs with the manufacturer's recommendations. In the long-term ecotoxicology trial with marine organisms, only the more robust ragworms with the lowest dose of biocidal FR antifoul paint particles survived. The LC-50 (i.e. when 50% mortality had occurred) for cockles with the biocidal SPC was 16.3 grams per litre after five days and for the biocidal FR, it was 23.3grams per litre after eight days.

Cleaning methods: In general, the HP jet cleaning method released less copper than either of the brushes. This was also true for the majority of the particle release counts, with the exception of the non-biocidal SPC that released fewer paint particles using the brushes than with the HP jets.

5.3. How much pollution could be expected to occur from one cleaning event?

The levels of dissolved copper and zinc found in water samples taken after each cleaning event in the current trial were, for the most part, below the European Water Framework limits.

While some level of biocide release can occur during in-water cleaning of biocidal coatings, it should also be put into the context of biocides released passively while a ship is docked or at anchor without cleaning occurring. At the highest levels of copper released during the current trial the average amount of copper released was calculated as the equivalent to that which may be released passively by a biocidal SPC , while simply moored alongside, during 0.61 of a day. Additionally, it should be noted that this report and indeed the manufacturers themselves, both recommend not using brushes at all for this particular coating.

Results from this trial indicate that foul release coatings, or any non-biocidal coating, pose an even lesser biocidal risk to the environment, as would be expected.

5.4. Remaining questions for inorganic pollutants

The following areas are considered by this study as information gaps that require attention to allow a thoroughly informed view of the relative risk of in-water cleaning to be determined, with a view towards the likely direction of travel in which the industry is moving:

- How do the experimentally derived paint particle and biocide data generated during this study compare to actual full-scale cleans?

- How do any localised negative environmental impacts associated with repeated hull cleaning compare to the benefits of vessels operating with clean hulls?

- How effective are closed circuit / capture in-water hull cleaning systems at preventing the paint debris described in this study from entering the marine environment under real world operational conditions?

- What are the long term (1, 5, 10+ yr) implications of high concentrations of inert paint particles typical of foul release coatings in marine sediments?

- If the marine industry is moving toward pro-active cleaning practices, what sort of impacts are associated with these alternative forms of hull cleaning?

6. Conclusion

While this report only presents a fraction of the total study, and many limitations are acknowledged, the data give clear indications, under realistic conditions, that while IWC may cause some removal of paint particles and biocides, the levels produced may not be in excess of those produced during passive release, if high performance coating and appropriate, compatible cleaning methods are used.

Proving Compatibility of Coatings and In-Water Cleaning Devices Utilizing ISO 20679

Anita Børve, Jotun, Sandefjord/Norway, anita.boerve@jotun.no
Henning Johnsen, Jotun, Sandefjord/Norway, henning.johnsen@jotun.no
Petter Korslund, Jotun, Sandefjord/Norway, petter.korslund@jotun.no

Abstract

The shipping industry is under pressure to reduce its environmental impact and carbon footprint, while also facing the threat of invasive aquatic species that can harm biodiversity and ecosystems. One way to address these challenges is to use a biofouling management solution that combines a specially designed coating with a proactive in-water cleaning robot. This solution aims to keep the hulls of ships clean and thereby reducing drag, fuel consumption and emissions, as well as preventing the spread of invasive species. The 2023 IMO Biofouling Guidelines emphasize the importance of compatibility between hull coatings and the equipment used for surface cleaning. Complementing this, the ISO 20679 standard outlines rigorous procedures for evaluating the performance of all types of in-water cleaning technologies. This paper presents insights and challenges encountered during the testing of compatibility between antifouling coatings and underwater cleaning equipment.

1. Introduction

The need to improve sustainability in the shipping industry is accelerating. The global industry must cut carbon emissions and protect the marine biodiversity. Reducing the accumulation of biofouling on ships' hulls limits the spread of invasive aquatic species and reduces fuel consumption and thereby carbon emissions from shipping.

The most efficient way of controlling biofouling on ship hulls is the use of antifouling coatings containing biocides and, in most cases, an antifouling coating is sufficient to keep the ship clean. In cases where the fouling protection fails due to especially challenging trade, changing operational profile or deviation in fouling pressure compared to what was expected during coating specification, cleaning of the hull might be necessary to remove biofouling to reduce fuel consumption and greenhouse gas emissions as well as limiting the spread of invasive aquatic species. With the increased focus on sustainability, reduced fuel consumption, emissions, cost and protecting the marine environment, ship and environmental data is more extensively being collected and used to monitor ship performance.

The focus is shifting from cleaning when a ship has collected a significant amount of fouling towards a more proactive approach which includes cleaning of ships at a low fouling rate (microfouling) to reduce the negative impact of marine fouling. This proactive cleaning has been increasingly advocated, e.g. by *Hunsucker et al. (2018)*, *Swain et al. (2020)*. Jotun has also been active in promoting a corresponding standard for in-water cleaning, *Oftedahl and Skarbø (2021), Oftedahl et al. (2022), Skarbø (2022)*.

Although proactive cleaning is preferred, traditional cleaning is still performed with the corresponding reduced performance, increased fuel consumption, greenhouse gas emissions and danger of transporting invasive species with potential negative impact on the marine ecosystem.

When performing a cleaning operation there will always be a risk of unwanted erosion and degradation of the coating surface to be cleaned. This risk increases with increasing level of fouling, especially when moving from microfouling to various degrees of macrofouling. The consequence of coating degradation can be increased coating roughness, resulting in increased drag and reduced vessel performance. Degradation of the coating can reduce the coating efficiency that may lead to increased refouling rate. It can also reduce the coating lifetime and lead to premature polish through of the coating and increased risk of fouling towards the end of the in-service period. In addition, erosion and degradation of the coating can lead to the potential release of coating residues into the surrounding water.

2. Regulations related to in-water cleaning operations and compatibility between Coatings and In-water cleaning systems

Several international and local regulatory bodies are working on development of guidelines, standards and policies related to in-water cleaning of ship hulls. They describe the need for compatibility between coatings and in-water cleaning systems to various degrees.

The 2023 IMO Biofouling Guidelines were adopted by the Marine Environment Protection Committee (MEPC) 80 in July 2023, *IMO (2023)*. The document describes factors to consider when choosing anti fouling coatings (AFC) and in-water cleaning (IWC) systems. The cleaning system should be 'compatible with the AFC to minimize the damage of the AFC', and 'the choice of AFC should be compatible with the cleaning technologies available to ensure both minimum biofouling growth as well as reducing the risk of damage to the AFC and the potential release of harmful waste substances to the environment'. We slowly see that the guidelines are being adopted. In Brazil the Brazilian Navy has updated their regulations for controlling and managing ships' biofouling to align with the 2023 IMO biofouling Guidelines. The requirements for in-water cleaning permits took effect June 2025, and the full enforcement will commence February 2026.

A separate IMO guidance related to in-water cleaning was approved by MEPC in April 2025, *IMO (2025)*. The purpose is to provide guidance on matters relating to in-water cleaning of ships, in line with 2023 Biofouling Guidelines. It is intended to support the global availability of safe and environmentally responsible in-water cleaning services to support the universal application of the 2023 Biofouling Guidelines. It includes guidance to coating manufacturers, in-water cleaning system manufacturers, service providers and ships with respect to determining compatibility between coatings and in-water cleaning systems. The guidance definition says, 'Compatibility means that an in-water cleaning system can operate on a coating without causing damage, which may vary with the fouling rating of the coated area. It states that in-water cleaning (IWC) systems, with or without capture, should only be used on compatible coating types. The compatibility between an IWC system and a coating, or a type of coating, should be determined and documented based on testing (in situ or ex situ) at specified fouling ratings.

ISO 20679 titled 'Testing of ship biofouling in-water cleaning systems' was published in January 2025, *ISO (2025*). The standard provides detailed and rigorous procedures for performance testing of all forms of ship in-water cleaning, all types of biofouling, and all external submerged surfaces. It includes testing protocols and describes how to report on the efficacy and safety of the IWC system.

The standard does not give any IWC performance requirements, as this is the responsibility of individual authorities, agencies, or administrations. Regarding compatibility between coating and IWC system, the standard states that observations of coating physical condition on various ship surface types before and after cleaning shall be recorded and reported. This could be by photos, videos, or both. It further states that the observations regarding the physical condition of the coating can include, but are not limited to, visible scratches, brush marks, paint flakes, pitting, bare metal/polish through, and blemishes. Repeated measurements of coating dry film thickness (DFT) are given as an optional method for determination of IWC impact on the coating.

3. Jotun's ambition

Since 1926 Jotun has been on a mission to protect property in every corner of the world. It began with a solution to protect ice going ships travelling to the Southern Ocean from corrosion. Today Jotun protects assets in a wide variety of industries and is a global market leader in marine coatings and hull performance solutions. Jotun's aim is to protect the environment and create value by contributing to customers' sustainability ambitions and goals. Jotun is committed to continuously innovate and develop advanced products and solutions designed to protect biodiversity and cut carbon emissions to support global sustainability ambitions and achieve cleaner operations for all industry players. Jotun has a range of services, products and digital capabilities solving customer challenges today. The Jotun Clean Shipping Commitment (www.jotun.com/no-en/industries/shipping) emphasizes the impact of a clean hull to reduce speed loss, ship down time, protect biodiversity, reduce fuel consumption and carbon emissions.

3.1. Jotun Hull Skating Solutions

Jotun has adopted proactive cleaning as part of the Jotun Hull Skating Solutions (https://www.jotun.com/no-en/industries/solutions-and-brands/hull-skating-solutions/overview). Jotun's Hull Skating Solutions are designed for operations where ships performance is lowered due to fouling and cleaning is required to keep a ship's performance, control biofouling and reduce the potential for release of invasive species. A primary component of Jotun Hull Skating Solutions is the unique, onboard HullSkater, the first robotic technology that has been purpose-designed for proactive cleaning. The solution includes a proactive ship in-water cleaning system designed to reduce growth on submerged ship surfaces and keep ships clean, as part of a ship's biofouling management program. In combination with the premium SeaQuantum Skate antifouling coating and a set of services, Jotun Hull Skating Solutions will help ship operators combat early-stage fouling, significantly reduce fuel costs, greenhouse gas emissions and hinder the spread of invasive species. SeaQuantum Skate has been developed specifically to optimize performance in combination with Jotun HullSkater. The coating is designed to endure repeated mechanical contact with the proactive cleaning unit on the HullSkater without eroding or damaging the coating.

3.2. Compatibility between coating and IWC solutions

Extensive testing has been performed during the development of the Hull Skating Solutions to evaluate and ensure the compatibility between SeaQuantum Skate and the HullSkater. Other Jotun coatings have also been evaluated after external IWC systems have been used.

3.2.1. The journey

The development of the Hull Skating Solutions related to water quality and compatibility has been a journey and a stepwise knowledge building. Moving from laboratory tests in controlled environment with mockup units, to indoor seawater basin for full scale testing with the HullSkater has been important, Fig.1.

Fig.1: Indoor seawater basin for large scale testing

Testing on raft, Fig.2, and on a test structure in the sea, Fig.3, has also been important before moving to testing on vessels in trade.

Fig.2: Raft panel large scale testing

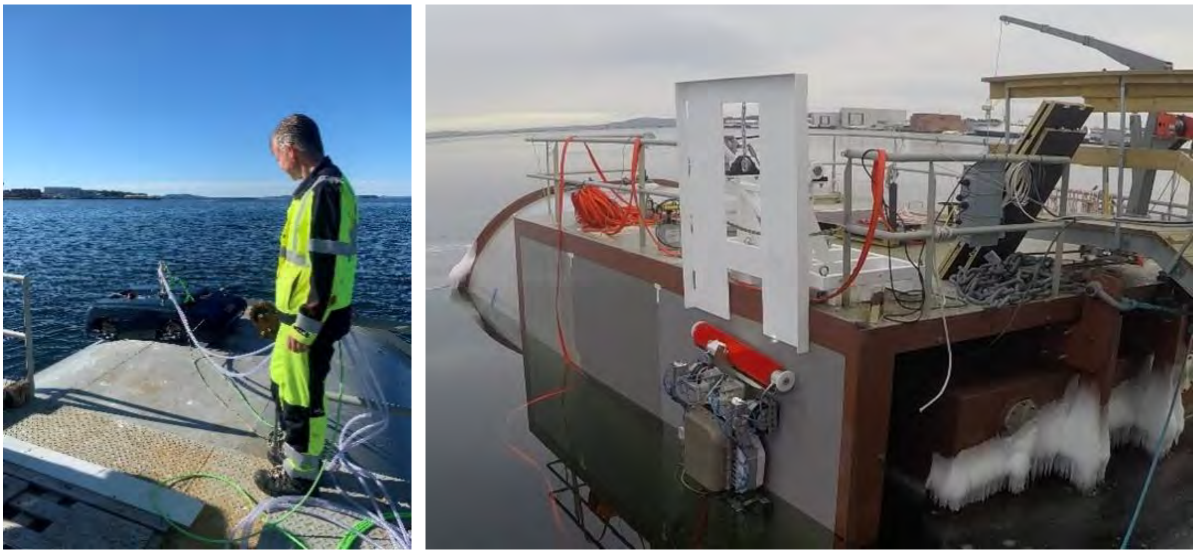

Fig.3: Testing on floating structure in the sea

The most important testing was done on vessels in-service, Fig.4. This included performance monitoring of pilot vessels in trade and water quality testing with third party, all leading to Lloyds Clean Hull Notation, https://www.lr.org/en/knowledge/press-room/press-listing/press-release/2025/lr-grants-industry-first-full-antifouling-approval-to-jotuns-hull-skating-solutions/.

3.2.2. Evaluation and quantification of compatibility

Evaluation and quantification of impact of an IWC system on a relevant coating surface is challenging, especially in tests performed on vessels in service. As described in ISO 20679, coating damage can be visually detected but is difficult to quantify from images or video unless the damage is severe.

Fig.4: Testing on vessels in service

Surface roughness has also been proposed as a method to detect the impact of cleaning equipment on a coated surface. This is easy to do on test panels but increasingly difficult on vessels. On vessels there will be variations in surface roughness over the vessel due to variable application quality. SPC coatings will also change surface roughness over time due to polishing, so out of dock roughness cannot be used as reference roughness. Increased roughness due to damages might be easier to quantify on a fouling release coating.

The best way to evaluate and quantify degradation of a coating due to cleaning is quantification of changes in dry film thickness. Our experience is that measuring total film thickness on a coated surface will not be good enough unless the degradation is severe and a large part of the coating is removed. The general problem is the large variation in film thickness after application by airless spraying. Even on small test panels there are rather big variations of the film thickness over the panel. The variations even in small areas are probably larger than the possible difference in film thickness before and after use of IWC equipment.

We believe the only way to get a true number of possible erosion is quantification of dry film thickness on crosscuts of paint flakes using a microscope. This is easy to perform on test panels when the panel can be cut in pieces before examining the crosscut as illustrated in Fig.5. The figure shows a crosscut of an antifouling film where the part on the right has been protected by a tape or a non-degradable coating keeping the film with the upper leached layer intact. To the left the surface has been subjected to erosion by cleaning, and parts of the leached layer have been removed.

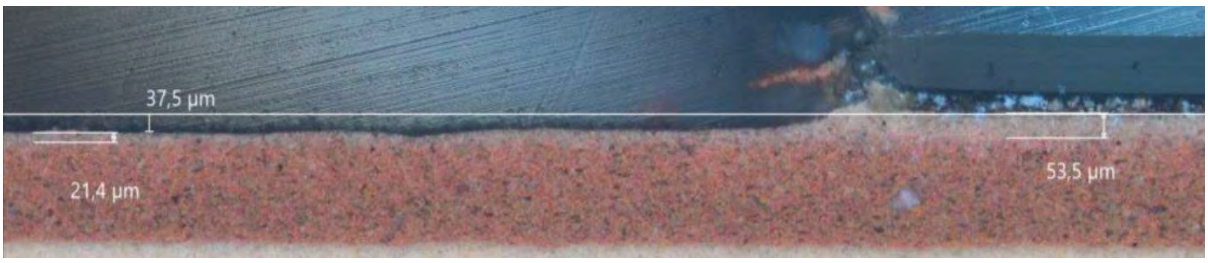

Fig.5: Microscope image of a crosscut of an antifouling film being eroded during cleaning

There are currently no easy and good methods to investigate the IWC equipment impact on the coating thickness when used on a vessel in service. Removing paint flakes from the same area before and after cleaning is difficult and costly to do in real life. It works best when a vessel has multi layers paint systems from several dockings but is more difficult for newly blasted vessel with paint system only from the ongoing docking interval.

4. Experience from utilizing ISO 20679

The water quality testing has been performed in full scale with the HullSkater on panels in the indoor test basin, on the static structure in the sea, and finally on vessels in trade. Testing has been performed on a selection of vessels to get a variation in trade and lifetime of the coating. The test schemes have been based on the ISO 20679 standard and the precursor, the ACT/MERC test procedure.

The assessment of the expected hull condition with regards to fouling was done by performing inspection in a port close in time prior to the testing or using reports from previous inspections. In-situ inspection of fouling on the hull was done during the cleaning operation. The cleaning efficiency was recorded in situ with live video, and video and photo material were stored for documentation.

The water samples were taken on the HullSkater while cleaning the underwater hull. Reference samples were taken on the HullSkater at test depth, in the water line alongside the ship as well as from the water line at key side in the harbour. Samples were collected from the sampling on the HullSkater via a hose connected to a sampling pump positioned onboard a support vessel alongside the test ship as illustrated in Fig. 6. Samples were collected in sample bottles for transport to and analysis at an external laboratory.

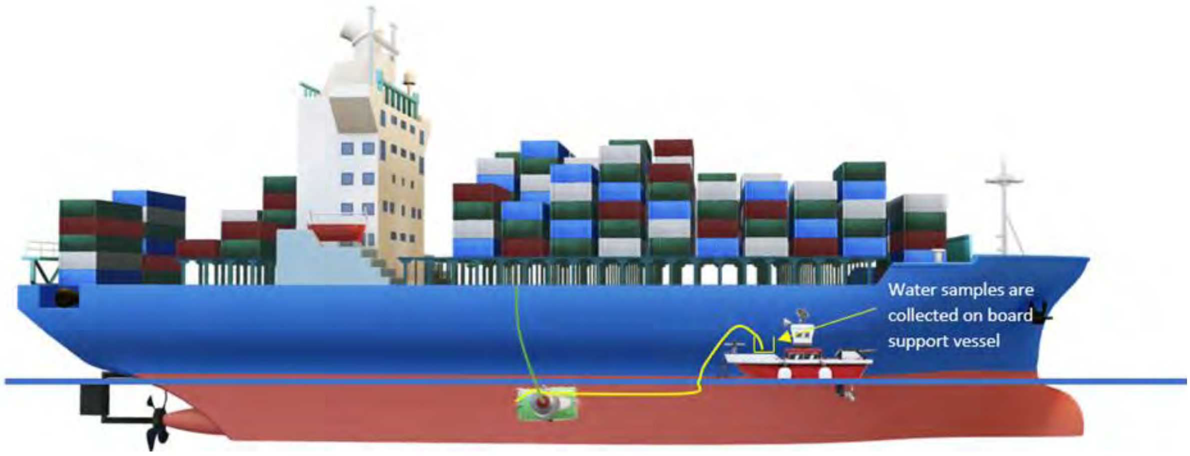

Fig.6: Collection of water samples via hoses connected to the HullSkater

Separate tests were performed as mentioned earlier to confirm no degradation of the coating during cleaning with the HullSkater. When performing water quality testing during cleaning of SeaQuantum Skate with the HullSkater little or no effect on concentrations of e.g. metals or particulate material in collected water samples during cleaning has been seen. This corresponds well with the tests analyzing film thickness on samples from compatibility testing performed in lab and on vessels in service showing no erosion of paint film.

Water quality testing is therefore considered to be a good method for testing compatibility and confirming no degradation. Water quality testing is less resource-demanding and easier to do for all IWC companies compared to compatibility testing with paint flake sampling and analysis.

The difficulty lies in defining what a significant increase in the values before, after and during testing are, and to correlate these increased levels of, e.g., metals to reduction in film thickness. From testing other Jotun paint systems on vessels in service with external IWC providers the experience shows that the levels of metals and particulate material show significant increase if the coating has been damaged or larger part of the coating is removed. It is challenging to establish a clear correlation between the increase in water quality values to a reduction in film thickness or the extent of degradation. Even more complex is linking these changes to a potential impact on antifouling performance and the overall lifetime of the coating.

One important learning has been that it is important to perform the testing on intact areas in good condition so that the potential material taken off is due to erosion and not due to coating defects such as flaking. If the reason for fouling is poor film conditions the resulting removal will be high and will not give a correct picture of the compatibility.

It is also important to have some kind of monitoring of impact on coating, either visual monitoring on the unit to see if coating is coming off or detection of paint residues in the collected water. This can be challenging depending on the amount of fouling coming off.

5. Conclusion

ISO 20679 is useful for documentation of compatibility between a coating and IWC systems, especially when the cleaning is done without any coating degradation. There is still no quantitative correlation between water quality numbers and degree of degradation or erosion. In addition, we still do not have an upper acceptable limit to what degradation is acceptable from a coating perspective, i.e. that does not affect the coating antifouling performance or lifetime.

Acknowledgement

Performing water quality testing during operation of the Hull Skating Solutions would not have been possible without world-class partners, which we gratefully acknowledge. Thanks also go to the many colleagues at Kongsberg and to our valued customer partners.

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Aligning Financial Incentives and Environmental Regulation: Integrating Hull Cleaning Waste into MARPOL Annex V

Alex Noordstrand, Fleet Robotics, Delft/The Netherlands, a.noordstrand@fleetrobotics.com

Abstract

In our previous PortPIC paper (Noordstrand, 2020), we showed that well-crafted environmental regulations can drive innovation in hull cleaning. This paper warns that emerging standards allowing capture-free cleaning of "light" biofouling risk environmental harm and weaken incentives for technological progress. We argue that fouling, even at low levels, carries risks of coating release and invasive species spread. To address this, we propose extending MARPOL Annex V with new categories for fouling residues and paint-contaminated filters, funded through the no-special-fee system, thereby aligning financial incentives with environmental protection and supporting sustainable industry growth.

1. Introduction

Fouling on ship hulls remains one of the most persistent operational and environmental challenges in shipping. While anti-fouling coatings based on biocides were designed to minimize fouling, their effectiveness depends heavily on operational profiles, idle times, application quality, and environmental conditions. As a result, even modern vessels accumulate fouling, which increases resistance and fuel consumption.

In practice, fouling distribution across a ship's hull is highly variable. Vertical sides are exposed to sunlight and often develop photosynthetic fouling such as algae, the flat bottom, where sunlight does not penetrate, typically harbours animal fouling such as barnacles. This heterogeneous distribution complicates regulation, as a vessel may be classified as having "light fouling" on the basis of certain surfaces, while substantial sections are in fact affected by macrofouling, leading to environmental risks due to misclassification or undetected fouling.

Operators increasingly rely on underwater cleaning to restore hull efficiency. Traditional methods, diver-operated brush carts or ROV's, remove fouling but also release paint particles, including toxic biocides, into the water when force is applied to the surface to remove fouling. In many ports and anchorages with limited enforcement, this situation has been described as the "wild west" of hull cleaning, *Noordstrand (2023).* The absence of incentives to capture residues leads to localized contamination of water and seabeds, as well as risks of spreading invasive species, which has prompted some authorities to ban underwater cleaning altogether.

Over the last decade, however, technologies with fouling capture capabilities have emerged. Several progressive ports have piloted these systems, allowing controlled in-port cleaning during cargo operations. This provides a potential "promised land" scenario where both environmental protection and operational efficiency can be achieved. Yet, in the absence of an international standard, each port or national authority continues to impose different requirements, resulting in uneven environmental outcomes and fragmented innovation incentives.

Building on the theoretical foundation of Porter's Hypothesis and the recommendations from our earlier PortPIC contribution, this paper argues for the integration of fouling residues into MARPOL Annex V. By adding clear waste categories and linking them to existing no-special-fee funding mechanisms, regulators can align economic and environmental incentives to accelerate innovation, improve compliance, and reduce the ecological footprint of the hull cleaning industry.

2. The Regulatory Risk

Recent lobbying by system developers and NGOs has sought to create a standard distinguishing microfouling from macrofouling, with the aim of permitting cleaning without capture when only light microfouling is present, *IMO (2023).* The rationale is that minimal cleaning effort poses negligible risks of coating release or invasive species transfer. However, this framing overlooks the real-world condition of hull coatings: even light cleaning often detaches paint particles due to routine wear and tear of the vessel such as grounding, corrosion, fender damage, paint application issues and chain damage. If this exemption is approved, capture-free cleaning could become widespread.

If such an exemption were to be implemented, the main barrier to effective governance would be enforcement. Monitoring fouling levels and ensuring compliance is operationally complex and resource intensive, which creates several specific challenges:

- Inspection constraints: Pre-cleaning inspections are costly, time-consuming, and logistically difficult to organize during narrow operating windows.
- Conflict of interest: Service providers often inspect and clean the same vessel, creating incentives to underreport fouling severity.
- Economic alignment: Both operator and service provider financially benefit from avoiding capture.

Without strong safeguards, this exemption risks undermining incentives for innovation and degrading environmental outcomes, echoing broader governance findings that self-regulation fails when compliance increases costs, *Gunningham and Sinclair (1999), OECD (2021).* The risk is a gradual institutionalisation of capture-free cleaning, eroding progress toward sustainability.

3. Lessons from MARPOL Waste Regulation

MARPOL Annex V provides a successful precedent. Before its adoption, ship-generated waste such as plastics, cooking oil, and incinerator ash was routinely dumped at sea. Annex V introduced harmonized waste categories (A–K), mandated Garbage Record Books, and established port reception facilities, *IMO (2017).* These measures fundamentally changed industry practice and governance. The impact has been transformative in several key ways:

- A global infrastructure for waste management emerged.
- Illegal dumping declined significantly.
- A level playing field was created between compliant and non-compliant operators, *GESAMP (2019).*
- Uniform rules prevented countries from competing by lowering standards, ensuring ports could not attract business through weaker environmental requirements.

These lessons highlight how clear definitions, integrated infrastructure, and standardized reporting can align economic activity with environmental protection. Fig.1 on garbage categories and disposal restrictions illustrates how regulation can be made both enforceable and practical in daily ship operations.

GARBAGE DISPOSAL RESTRICTIONS
(OUTSIDE POLAR REGION)

Cat.	Garbage Type	Garbage Disposal at Sea (Outside Special Areas)	Garbage Disposal at Sea (Within Special Areas)	Receptacle Colour
A	Plastics	Discharge Prohibited	Discharge Prohibited	Red
B	Food waste comminuted or ground[1]	>3 nm from the nearest land, enroute and as far as practicable[4]	>12 nm from the nearest land, enroute and as far as practicable	Blue
	Food waste not comminuted or ground	>12 nm from the nearest land, enroute and as far as practicable[4]	Discharge Prohibited	
C	Domestic Wastes	Discharge Prohibited	Discharge Prohibited	Black
D	Cooking Oil	Discharge Prohibited	Discharge Prohibited	White
E	Incinerator ashes	Discharge Prohibited	Discharge Prohibited	Green
F	Operational Wastes	Discharge Prohibited	Discharge Prohibited	Yellow
	Cleaning agents or additives in cargo hold wash water (NON-HME).	Discharge Permitted[5]	Discharge only permitted in compliance with Marpol Reg. 6.1.2 [2]	N/A
	Cleaning agents or additives in deck and external surface wash water (NON-HME).	Discharge Permitted[5]	Discharge Permitted[5]	
G	Animal Carcasses	Discharge permitted Must be en route and as far from the nearest land as possible. Should be >100 nm and maximum water depth	Discharge Prohibited	N/A
H	Fishing Gear	Discharge Prohibited	Discharge Prohibited	N/A
I	E-Waste	Discharge Prohibited	Discharge Prohibited	Silver
J	Cargo residues[3] not contained in wash water. (NON-HME)	> 12 nm from the nearest land, enroute and as far as practicable	Discharge Prohibited	Grey
	Cargo residues[3] contained in wash water. (NON-HME)		Discharge only permitted in compliance with Marpol Reg. 6.1.2 [2]	
K	Cargo Residue (HME)	Discharge Prohibited	Discharge Prohibited	Orange
	Mixed Garbage	When garbage is mixed with or contaminated by other substances prohibited from discharge or having different discharge requirements, the more stringent requirements shall apply		

Fig.1: Garbage types with disposal restrictions, *Seaman Guide (2020)*

4. Proposal: New Categories for Hull Cleaning Waste

We propose extending Annex V with two additional garbage types that specifically address the waste streams generated during underwater hull cleaning. At present, these residues fall outside established categories, creating legal ambiguity and uneven enforcement. By formally including them, MARPOL would close this regulatory gap and provide a uniform global framework:

1. Category L: Fouling Residues: organic material removed from hull surfaces such as algae, barnacles, mussels, seagrass, and other marine growth. In practice, these residues are often mixed with paint particles released during cleaning, making them comparable to light chemical waste that requires controlled treatment. They may also contain invasive species that can alter local ecosystems if discharged untreated.
2. Category M: Paint-Contaminated Filters: filter media used in capture and treatment systems. These filters primarily retain organic fouling material but are frequently contaminated with paint particles, particularly from self-polishing antifouling coatings. As a result, they often

contain biocides and must be collected, handled, and disposed of as light chemical waste, even when the level of contamination varies.

Formally recognizing fouling residues and paint-contaminated filters as new MARPOL Annex V categories would close the current regulatory gap and create a uniform global framework. Such a step would bring regulatory clarity by explicitly defining hull cleaning residues as waste, while at the same time enabling integration into existing port reception facilities so that treatment and disposal are managed through established infrastructure.

5. Financial Mechanism and Industry Impact

The no-special-fee model is a port-based funding mechanism in which all ships calling at a port or major anchorage region for services pay a flat, mandatory waste fee regardless of whether they actually deliver waste to the port reception facility. In return, basic waste collection and treatment services are included at no additional charge. This removes the incentive for ships to illegally discharge waste at sea to save costs. Extending this model to fouling waste would also ensure that part of the collected revenue is allocated as compensation to certified service providers, covering the costs of capture, transport, and treatment of residues. Extending this model to hull cleaning waste would:

- Create stable funding streams for service providers to invest in capture, filtration, and transport technologies.
- Lower enforcement costs by embedding hull cleaning waste into established inspection and recordkeeping systems.
- Ensure a level playing field, so compliant service providers are not undercut by cheaper, non-capturing competitors.

A key issue that creates an unequal playing field between hull cleaning with and without capture is the cost of wastewater capturing and treatment. Captured residues frequently contain paint particles with biocides and heavy metals, making them comparable to light chemical waste that requires certified processing. Such treatment is costly, with disposal prices per cubic meter of wastewater far exceeding those of ordinary port waste. This cost burden creates a perverse incentive: the more waste service providers capture, the more they must pay. Embedding fouling waste into the no-special-fee framework corrects this imbalance. The ship, as polluter, contributes via a universal port fee, while service providers can rely on specialized waste handlers for safe treatment and disposal.

From a broader perspective, this reform directly reflects Porter's Hypothesis: well-crafted regulation not only reduces environmental harm but also stimulates technological advancement and competitiveness, *Porter and Van der Linde (1995).*

6. Conclusions and Recommendations

Unless addressed, the proposed microfouling exemption risks legitimizing capture-free cleaning for much of the global fleet, creating long-term environmental harm and disincentivizing innovation. Integrating fouling waste into MARPOL Annex V offers a feasible, enforceable, and industry-friendly solution. To achieve this, each stakeholder group has a distinct role to play:

- IMO Working Groups: Evaluate technical and legal feasibility of adding categories for hull cleaning waste to MARPOL Annex V.
- Port Authorities: Upgrade reception facilities to handle hull cleaning waste.
- Regulators: Implement no-special-fee funding models to ensure polluters pay while maintaining fair competition. The fee for hull cleaning waste must be set at a level that covers the full cost of capture and treatment, ensuring the new waste categories are adequately compensated.
- Standards Bodies: Harmonize hull cleaning standards with MARPOL waste handling obligations to close regulatory loopholes.

- Industry Stakeholders: Collaborate with ports and regulators to pilot best practices and refine technologies.

By embedding environmental responsibility into the financial and operational structure of hull cleaning, regulators can ensure that sustainability and competitiveness reinforce one another. This creates a pathway out of today's fragmented "wild west" scenario toward a global, innovation-driven, and environmentally responsible hull cleaning industry.

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Experiences by Simulating In-Water Cleaning in the Lab (Taber) and in the Field (Brushes)

Bernd Daehne, Dr. Brill + Partner, Norderney/Germany, bernd.daehne@brillantifouling.com
Lukas Kuhn, Dr. Brill + Partner, Norderney/Germany, lukas.kuhn@brillantifouling.com
Soyla Kraus, Dr. Brill + Partner, Norderney/Germany, soyla.kraus@brillantifouling.com

Abstract

Cleaning on hard coatings is a promising solution for the future in protecting ship´s hulls from biofouling, marine ecosystems from invasive species, the sea from biocides, and the climate from greenhouse gases. But it is very important that the coatings resist the cleaning methods without being damaged and without the release of microplastics into the sea. The usual methods for assessing durability are abrasion tests according to Taber or tests with brushes in the lab. However, the conditions in the field differ from the lab. Dr. Brill + Partner, at its Institute for Antifouling and Biocorrosion on the North Sea island of Norderney, conducted comparative studies on the resistance of hard coatings by Taber abrasion under dry and under wet conditions, that simulate the real conditions of In-Water Cleaning much more realistically. In addition, comparative brush cleaning was carried out with and without initial biofouling.

1. Introduction

Proactive Cleaning on Cleaning-Resistant Coatings (CRCs) seems to become more and more used in protecting ship´s hulls from biofouling. This method has several advantages for both the economy and the ecology. However, it must be ensured that the resistance of such CRCs is correctly evaluated. Otherwise ship owner might get an unpleasant surprise when the coatings on their vessels will wear out more quickly than expected.

The usual methods for evaluating the resistance of coatings are abrasion tests by Taber or by brushes in the lab. A Taber abrasion test under dry conditions is currently done in the lab for e.g. automotive coatings but also for Lloyd's Ice class coatings, *LR (2021)*.

The young market of proactive brush cleaning on CRCs also conducts tests on unfouled plates in the lab. First simulated field tests with regular brush cleaning on fouled panels have been carried out in the research projects ROBUST (Funding Code 03SX490) and BioSHIP (Funding Code 03SX625) both funded by the German Federal Ministry for Economic Affairs and Energy. These investigations have shown that the conditions in the field differ distinctly from the lab. This was the catalyst for this more detailed study on the subject.

2. Methods

2.1. Test coatings

Tested were nine different coatings of which eight are commercially available and one shortly before market launch, Table I. Of these nine coatings three were primers, three topcoats with easy-to-clean properties, two topcoats without easy-to-clean properties and one barrier coating, Table II.

Each of the coatings was applied to two 9,8 mm x 9,8 mm x 1 mm steel plates with a center hole for Taber testing as well as two 200 mm x 200 mm x 1 mm for brush testing. Except for Coat.9, which was applied directly by the manufacturer, all coatings were applied by Dr. Brill + Partner according to the manufacturer's specifications. All coatings were left to cure for at least 14 days to ensure a fully cured product is tested.

The following report shows the results of the individual coatings in coded form.

Table I: List of the tested products sorted by manufacturer (alphabetically)

Manufacturer	Product	System
BaJo-Coatings	Ecokinetic	2K
	Ecokinetic+	2K
Clean Ocean Coatings	Clean Ocean Coating	--
Durepox	2K-Primer black	2K
	High Performance Clear	2K
Hempel	High Protect II	2K
	Light Primer	2K
International	Interprotect	2K
West System	West Epoxy + graphite powder	2K + additive

Table II: Overview of the test specimens in order of testing and their associated product categories. Anonymisation was carried out to ensure competitive neutrality and to comply with project-related confidentiality agreements.

Code	Category
Coat.1	Primer
Coat.2	Barrier coating
Coat.3	Primer
Coat.4	Easy-to-clean topcoat
Coat.5	Easy-to-clean topcoat
Coat.6	Topcoat
Coat.7	Primer
Coat.8	Topcoat
Coat.9	Easy-to-clean topcoat

2.2. Taber-Test

In the Taber Test, two scenarios were compared: The first scenario corresponds to the standard Taber abrasion test (ASTM D 4060). In this test, a test plate is tested under dry conditions in the Taber, the grinding dust is vacuumed off. The second scenario corresponds to the dry test in all parameters, with the difference that no grinding dust is vacuumed off, but instead the test plates are covered with water, which is continuously replaced. The general parameters for this test were defined based on the Lloyds ice class standard, *LR (2021)*: The tests were carried out with the CS-17 abrasive wheels and a weight of 1000 g for 1000 cycles. The abrasive wheels were reconditioned after every 500 cycles with P150 sandpaper for 50 cycles. These parameters applied to both the dry and wet tests. For the dry tests and the reconditioning of the abrasive wheels, the vacuum was set to 100% power.

For the wet test, a device was developed to ensure that the test plates were wetted and to prevent the formation of grinding sludge. This device allowed fresh water to be pumped into the specimen mount onto the test plate by the first pump, while the second pump extracted the excess water, Fig.1. Peristaltic pumps were used because they are self-priming, can run dry, have few problems with wear caused by abrasive particles and – in case wear becomes a problem - are easy to maintain.

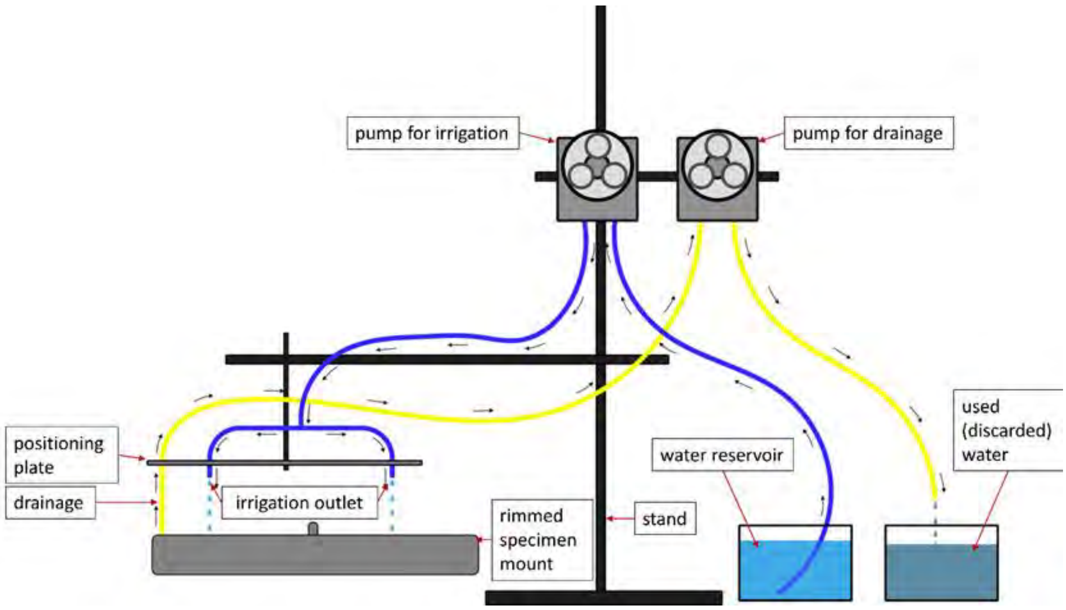


Fig.1: The irrigation apparatus: The first pump delivers fresh distilled water and drips it onto the abrasion area (blue lines). The second pump sucks the excess water from the edge and pumps it into a second container (yellow lines).

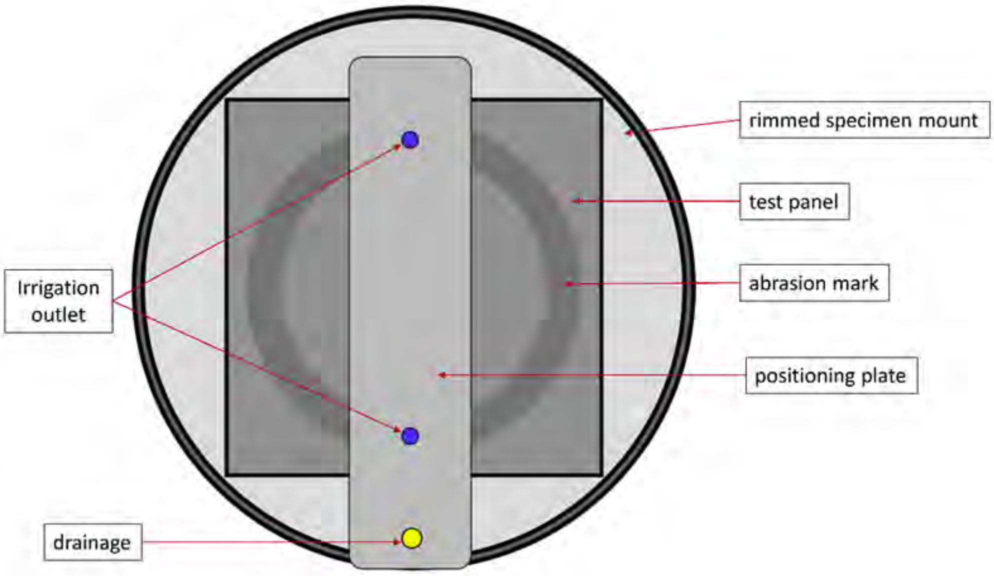


Fig.2: Alignment of the irrigation and drainage in relation to the test panel and the specimen mount

The two outlets for the irrigation were placed directly above the abrasion area, one at the front and one at the back between the abrasion wheels to flush away the abraded material. The drainage was positioned at the edge of the specimen mount where the water piled up due to the rotation, Fig.2. This way, its height could be adjusted in a way that only the excess water, which would otherwise be thrown out by the centrifugal forces, would be sucked off. By doing so, the maximum possible amount of water was always present in the mount and thus on the test panel. The irrigation pump was set to supply approximately 100 ml per minute so that the water in the mount was changed three times per minute. To prevent spillage, the drainage pump was set slightly faster than the irrigation pump. The test panels were placed in distilled water one hour before the test to allow them to adapt to the conditions.

To evaluate the abrasion, it was decided to measure the thickness of the coating before and after the Taber-treatment. Therefore, the coatings were applied to metal plates as a substrate. The thickness was measured with a PCE-CT-80 thickness meter with a F2D5 probe.

In order to ensure the same spot is measured before and after treatment, a template was made. The template allowed measurements to be taken at 12 different points on the (soon to be) abraded area, Fig.3. The diameter of the holes in the template corresponds to the diameter of the probe, so that the measurements can be taken with only minor local deviations. A mark in the upper left corner ensured that the same points are measured before and after treatment in the Taber. Each position was measured three times before and after treatment. The mean value is then calculated from these three measured values, which is then used to calculate the abrasion for each of the 12 points on each panel. The average abrasion for the entire plate was then calculated from these 12 abrasion values.

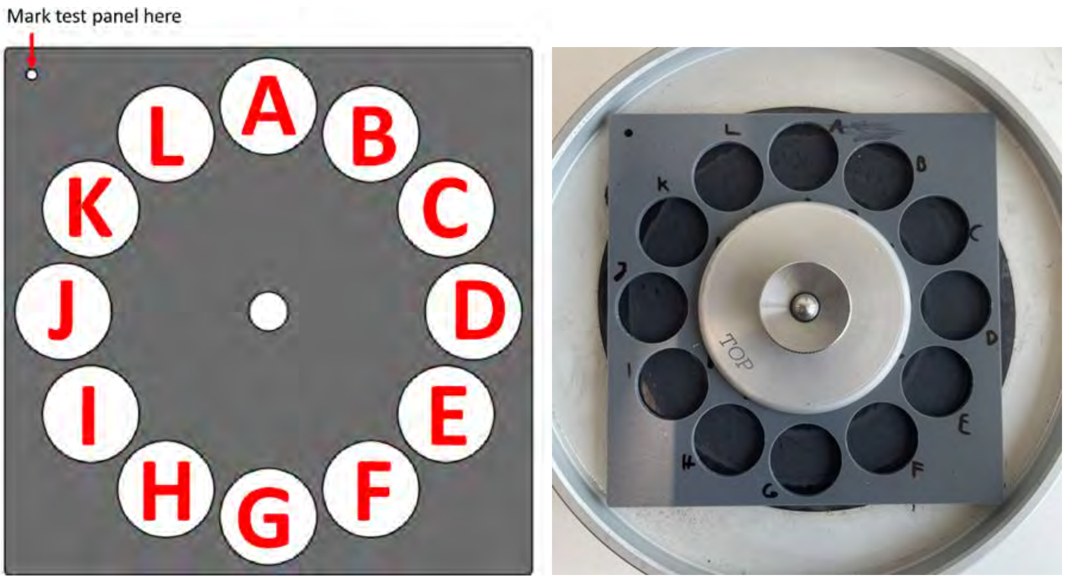


Fig.3: Schematic drawing of the template for thickness measuring (left) and the template fixed to the test panel on the specimen mount during measuring (right). To ensure, the measuring points before and after treatment correspond, the test panel is marked in the top left corner.

2.3. Cleaning-Test by brushes

At the brush-test, again two scenarios were compared: In the first scenario without biofouling test panels have been immersed in distilled water in the lab for four weeks before brush cleaning has been conducted by using a cordless screwdriver fitted with an extra soft brush under wet conditions for 10 s per panel, Fig.4, Fig.5.

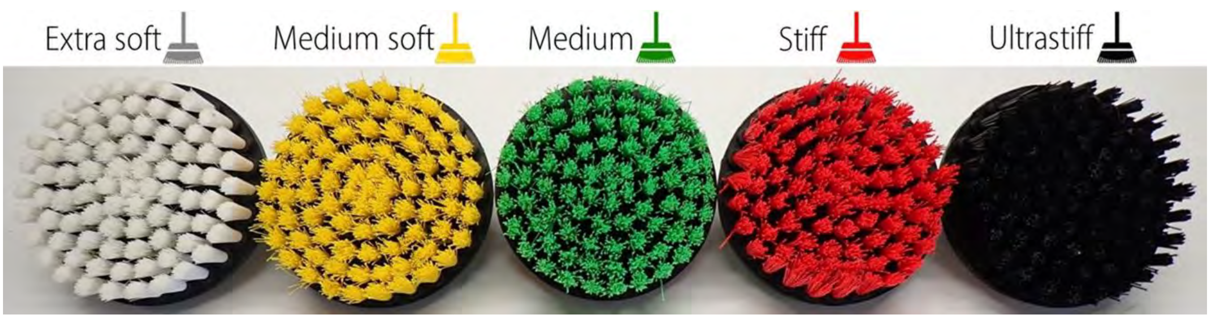


Fig.4: Brushes with increasing hardness

The second scenario was conducted with replicate panels of the same coatings. Coat.1-8 have been immersed in the North Sea for three weeks (July 1^{st} – 21^{st}) before being cleaned again under permanent wet conditions with the extra soft brush for 10 s per panel. Coat.9 has been immersed for 4 weeks (April

24th – May 28th). These panels had typical initial biofouling after that period in the North Sea summer, and it would be the latest option for proactive grooming.

Grooming/Cleaning has been conducted in the same way by using a cordless screwdriver and only the extra soft brush for 10 s.

Fig.5: Simulated brush-cleaning at wet conditions

3. Results

3.1. Taber-Test

It was found that, despite the continuous water exchange, the wet tests were more abrasive than the dry tests, Fig.6. On average, dry testing abraded 47.39 µm while wet testing abraded 83.87 µm, Table III. This phenomenon occurred to varying degrees with all coatings tested. The biggest absolute difference between wet and dry testing was Coat.4 with 71.8 µm abrasion difference between the treatments. The ratio between dry and wet abrasion was highest in Coat.3 at 1:2.6. The smallest absolute difference as well as the smallest ratio had Coat.8 with a value of 4,61 µm in abrasion difference and a ratio of 1:1,1 between dry and wet testing. A look at the different types of coatings shows that those categorised as 'primers' were most affected by the wet tests. The ratio for these three coatings ranged from 1:2.21 (Coat.7) to 1:2.6 (Coat.3). But while Coat.1 and Coat.3 had quite high abrasion rates (dry: >40 µm; wet: >110 µm), the third primer, Coat.7 had nearly half that abrasion rate (dry: <30 µm; wet: <65 µm). Coat.9, an easy-to-clean topcoat, also should be mentioned here, since it had the lowest abrasion rates by far (dry: 10 µm; wet: 18 µm), the ratio on the other hand was the highest of all topcoats (1:1.79).

On average, the difference between wet and dry tests was 36.48 µm and the ratio between dry and wet abrasion was 1:1.83.

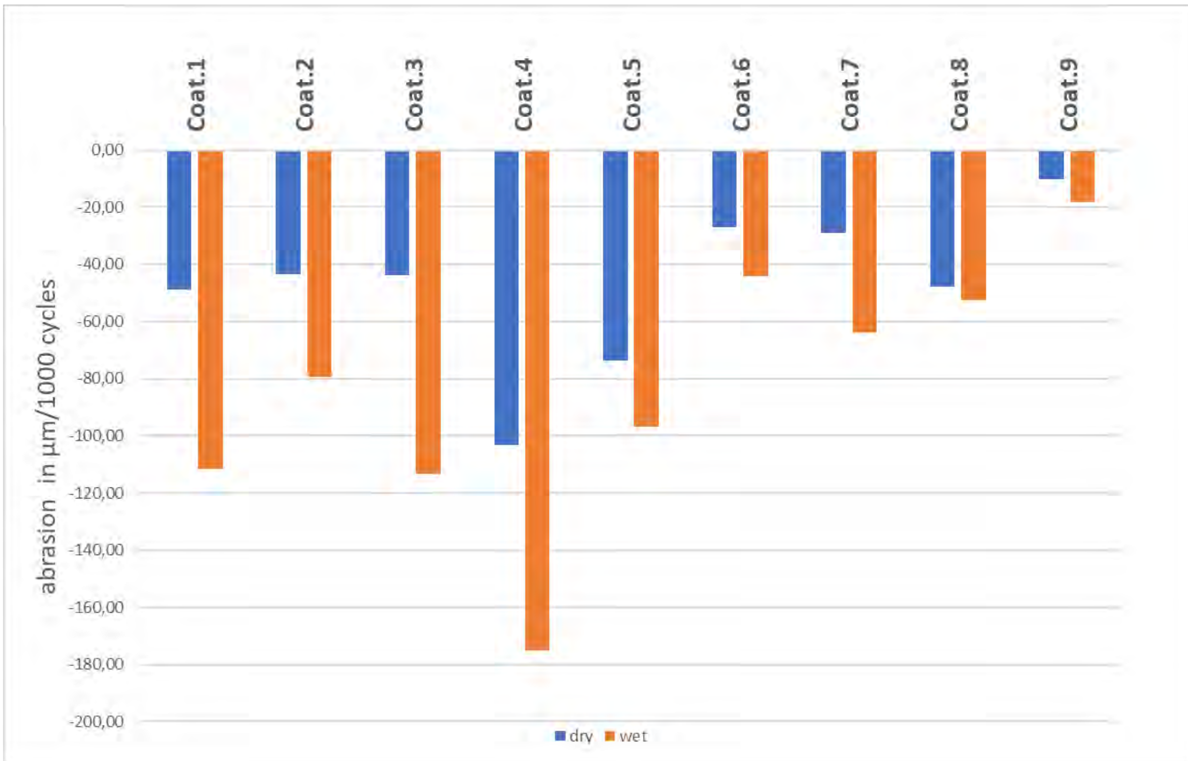


Fig.6: Abrasion after 1000 Cycles in the Taber Abraser (mean values). The "wet" value for Coat.4 has been calculated from 784 cycles, when the test was stopped. The more aggressive abrasion under wet conditions becomes visible throughout all coatings.

Table III: Abrasion of the wet and dry Taber test. On average, wet testing was 1.83 times more abrasive than dry testing

Name/Code	Category	Abrasion /1000 cycles in µm		Difference [µm]	Factor
		dry	wet		
Coat.1	Primer	-48,75	-111,54	62,79	**2,29**
Coat.2	Barrier coating	-43,28	-79,33	36,06	**1,83**
Coat.3	Primer	-43,67	-113,39	69,73	**2,60**
Coat.4	Easy-to-clean topcoat	-103,23	-175,03	71,80	**1,70**
Coat.5	Easy-to-clean topcoat	-73,56	-96,94	23,38	**1,32**
Coat.6	Topcoat	-27,14	-44,03	16,89	**1,62**
Coat.7	Primer	-28,88	-63,90	35,02	**2,21**
Coat.8	Topcoat	-47,78	-52,39	4,61	**1,10**
Coat.9	Easy-to-clean topcoat	-10,19	-18,28	8,08	**1,79**
Mean:		**-47,39**	**-83,87**	**36,48**	**1,83**

Most testing went according to plan. The only interruption was the easy-to-clean coating Coat.4, as it stood out somewhat. During the dry test of Coat.4, the abrasive wheels quickly turned black and large flakes of the coating came off. After around 400 cycles, no more flakes occurred. For this, metal substrate became visible after 729 cycles. After 912 cycles, the completely abraded area had increased, Fig.7. However, the flaking was most likely due to an application error, whereby the two layers of paint did not bond properly. The flakes probably were from the topmost layer being torn off.

When tested wet, the same flakes as in the dry test formed. After 145 cycles, these flakes had clogged the drainage pump thus the test was interrupted and the specimen mount as well as the pump were flushed. Thereafter no more flakes formed. After 619 cycles, first spots of bare metal substate occurred. After 784 cycles the test was ended, since nearly all coating had disappeared from the abrasion area Fig.8. The measurements of these abraded areas were not included in the mean abrasion values. For better comparability, the mean abrasion value was extrapolated to 1000 cycles for the wet test.

Fig.7: The dry tested Coat.4 test panel after 729 cycles (left) and 912 cycles (right) in the Taber Abraser. At measuring points B and C, the coating was completely worn away. These points were not included in the mean values.

Fig.8: The wet tested Coat.4 test panel after 619 cycles (left, still wet) and 784 cycles (right, dried) in the Taber Abraser. At measuring points B, C, D, E, F, I, J, and K, the coating was completely worn away. These abraded points were not included in the mean values.

During testing it became clear, that the abrasive wheels also undergo severe wear. They lasted for appr. 10.000 test cycles before they had to be replaced. The aluminum oxide or silicon carbide particles from the wheels accumulated at the outer bottom of the specimen mount during wet testing, Fig.9.

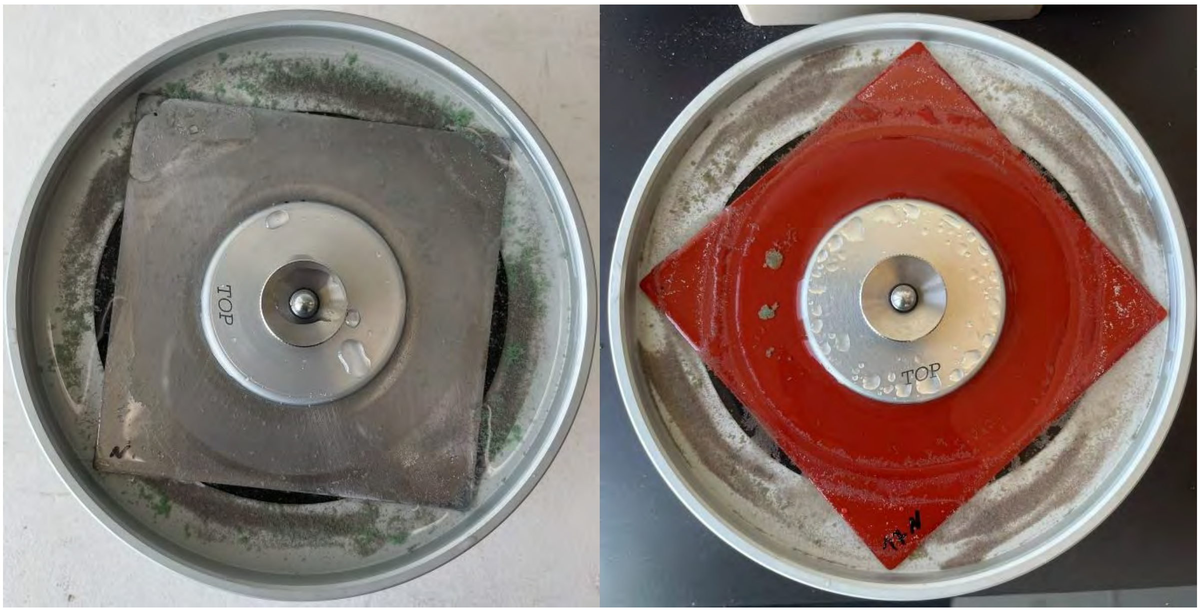


Fig.9: The Coat.6 and Coat.9 test plate after 1000 cycles in the Taber Abraser still in the mount covered in water. Nearly all debris seen here originated from the abrasive wheels.

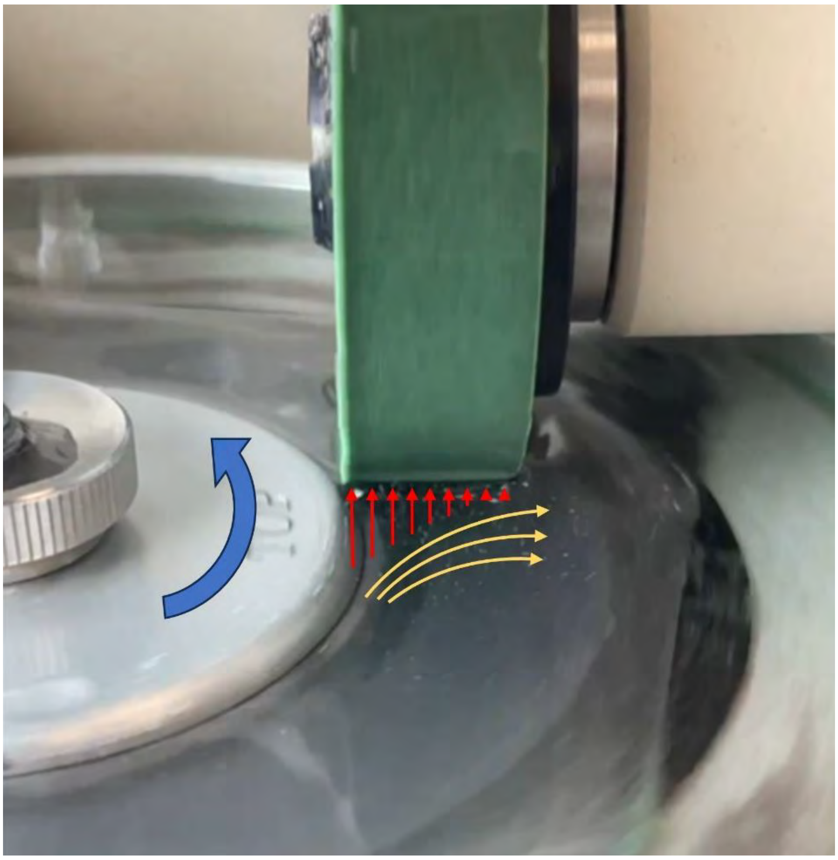
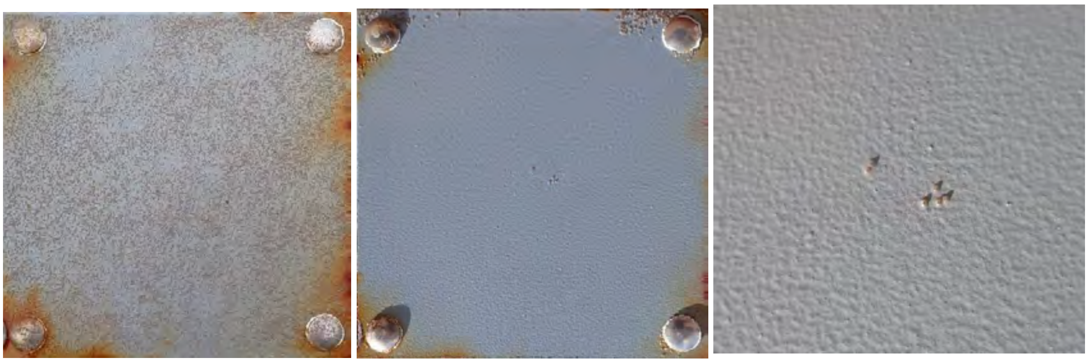


Fig.10: The right abrasive wheel while testing Coat.6. Loose abrasion particles from the wheel are flushed off the wheel after one rotation. Particles landing in the area marked red are drawn back under the wheel. Particles landing in the area marked yellow are washed away. The blue arrow marks the rotation direction.

Any loose particles, as well as those that were still loosely adhering to the wheels, were removed mostly after one rotation by the water that had built up in front of the abrasive wheels. They were then flushed off the panels by the water and the centrifugal forces. However, closer inspection revealed that most but not all these particles were flushed off the test panel. Some of the particles washed off the abrasive wheels were immediately drawn back under the same. This occurred in particles that found themselves flushed within a triangular zone in front of the wheel. That triangular zone gradually narrowed from the inside to the outside along the contact patch of the wheel. Particles landing outside of this triangle further away from the abrasion wheel were washed off the plate before they had the opportunity to get under the wheel again, Fig.10.

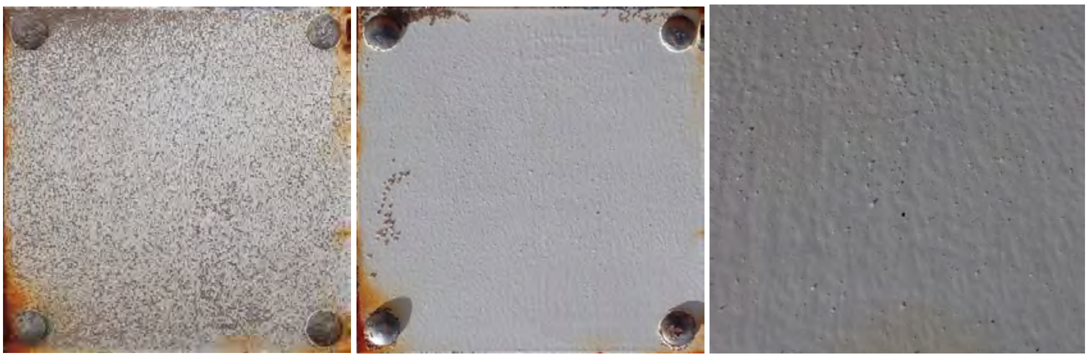
3.2. Cleaning-Test by brush

After three weeks of immersion at the DBP beach station in the Wadden Sea near Norderney, all panels had a dense cover with barnacle seeds and very small juvenile barnacles. Coat.9 had been exposed a little earlier in the harbour of Norderney for four weeks. It showed similar barnacle fouling and additionally some small algae. Besides some edge effects cleaning was successful at all coatings even with the extra soft brush. But concerning abrasion of the coating, some differences occurred, Fig.11-13.



Coat.1 – initial biofouling after 3 weeks - Close-up shows no visible damages.

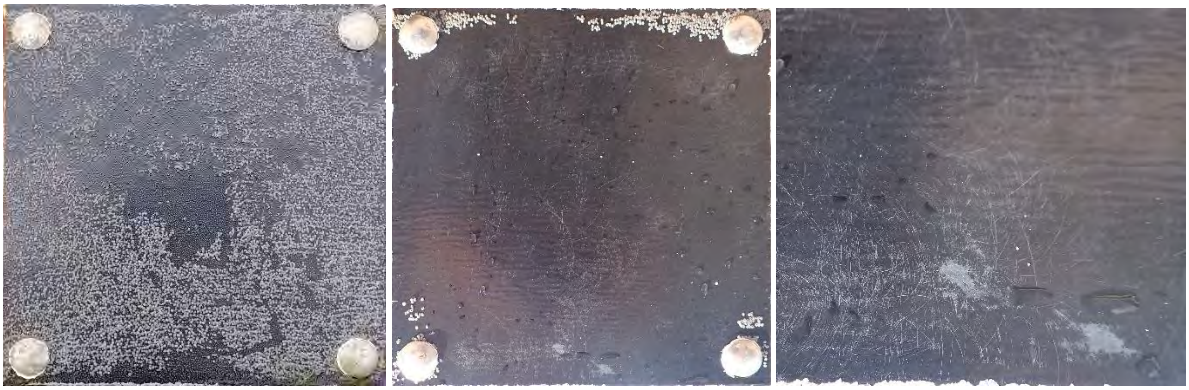
Coat.2 – initial biofouling after 3 weeks – cleaned - Close-up shows no visible damages.



Coat.3 – initial biofouling after 3 weeks – cleaned - Close-up shows no visible damages.

Fig.11: The test coatings Coat.1-3 before - after cleaning with extra soft brush for 10 s – close up pictures of the surface after cleaning.

Coat.4 – initial biofouling after 3 weeks – cleaned - Close-up shows no visible damages.



Coat.5 – initial biofouling after 3 weeks – cleaned - Close-up shows a lot of circular scratches and abrasion caused by detritus of the small barnacles.

Coat.6 – initial biofouling after 3 weeks – cleaned - Close-up shows circular scratches caused by detritus of the small barnacles.

Fig.12: Test coatings Coat.4-6 before - after cleaning with extra soft brush for 10 s – close up pictures of the surface after cleaning.

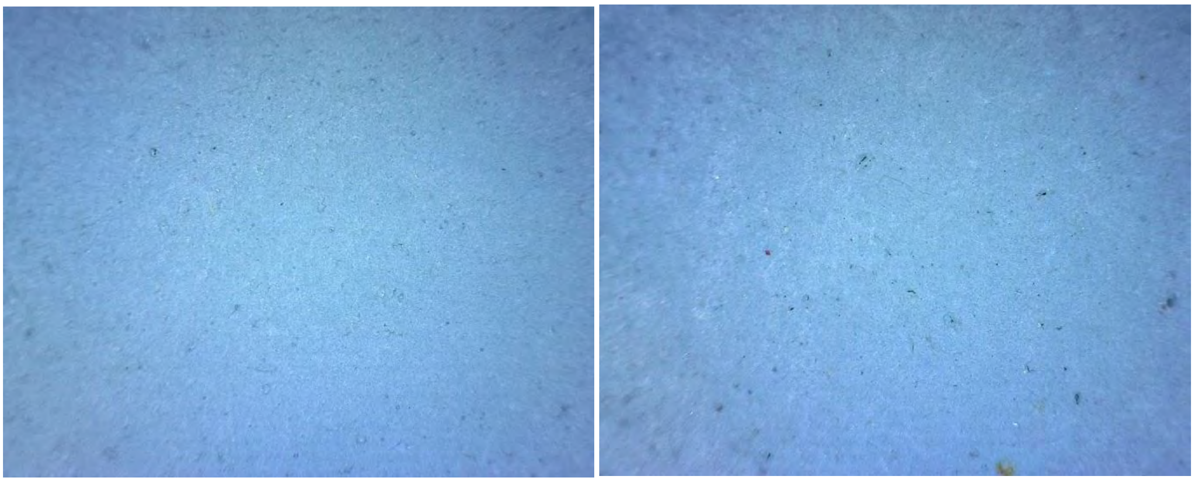
Coat.7 – initial biofouling after 3 weeks – cleaned - Close-up shows abrasion.

Coat.8 – initial biofouling after 3 weeks – cleaned - Close-up shows a lot of circular scratches caused by detritus of the small barnacles.

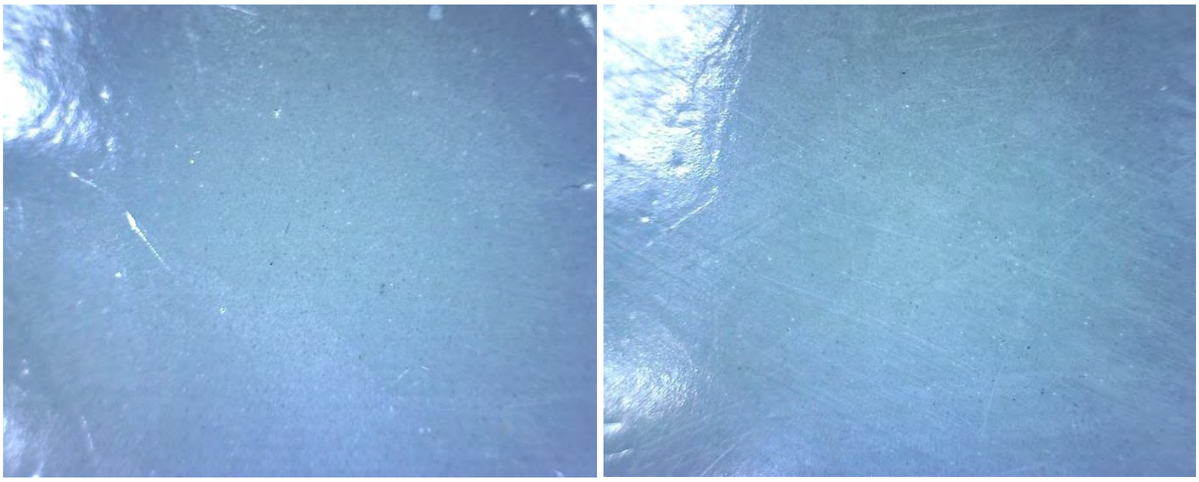
Coat.9 – initial biofouling after 4 weeks – cleaned - Close-up shows a lot of circular scratches caused by detritus of the small barnacles.

Fig.13: The test coatings Coat.7-9 before - after cleaning with extra soft brush for 10 s – close up pictures of the surface after cleaning.

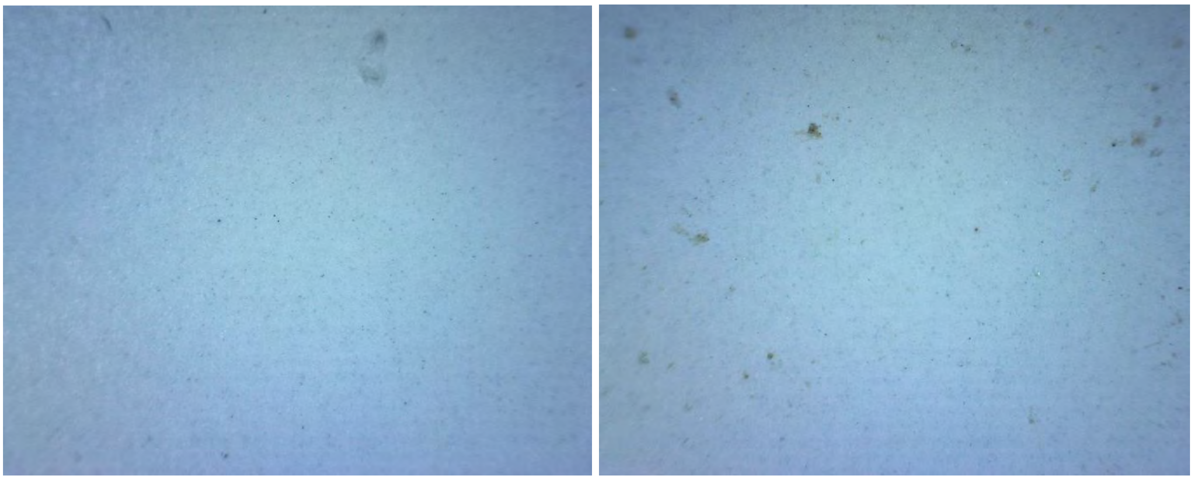
For a more detailed comparison additional photos were taken of Coat.1-8 under a microscope with 36x magnification with both replicates, from the lab without biofouling and from the field with initial biofouling, Fig.14 and 15. All tested coatings showed no scratches or abrasion at clean surface conditions without biofouling. But after cleaning with the same extra soft brush on coatings with initial biofouling five out of eight coatings had distinct scratches.



Coat.1 – surface after cleaning without biofouling (left) and with initial biofouling (right): No scratches visible.

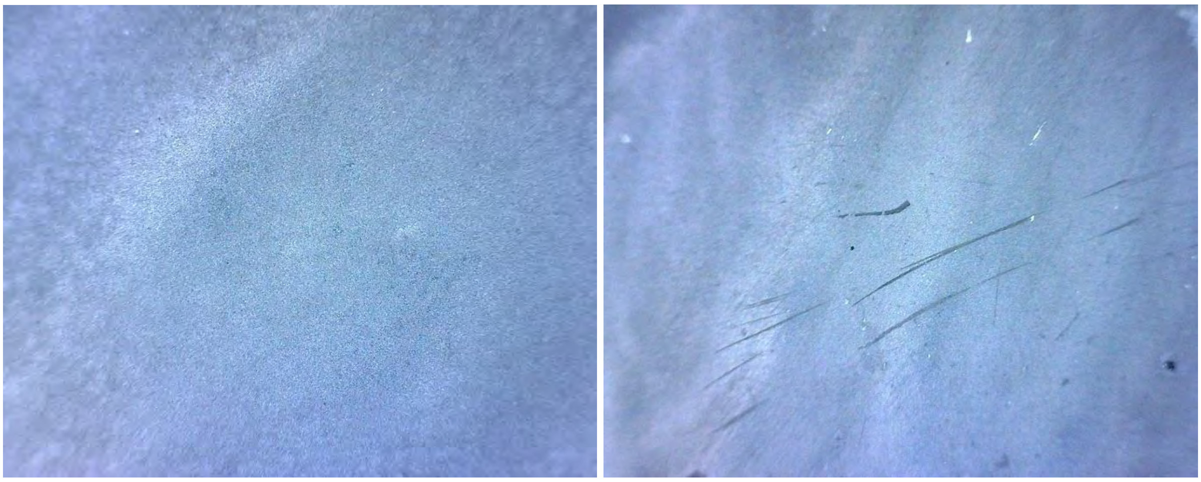


Coat.2 – surface after cleaning without biofouling (left) and with initial biofouling (right): Slight scratches visible.



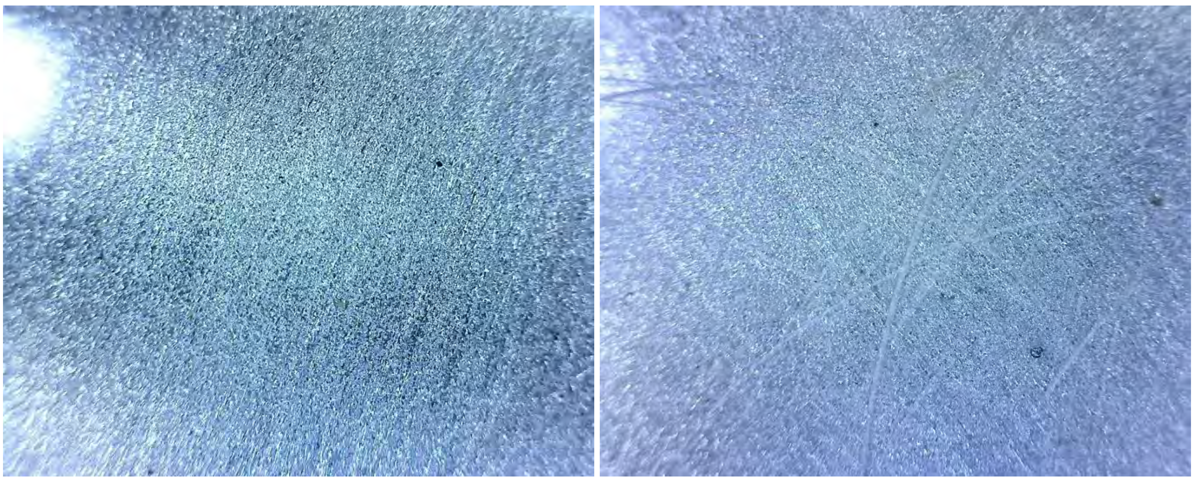
Coat.3 – surface after cleaning without biofouling (left) and with initial biofouling (right): No scratches visible.

Fig.14: Close-up pictures of the surfaces of test coatings Coat.1-3 after cleaning with extra soft brush for 10 s without biofouling (left) and with initial Biofouling (right).



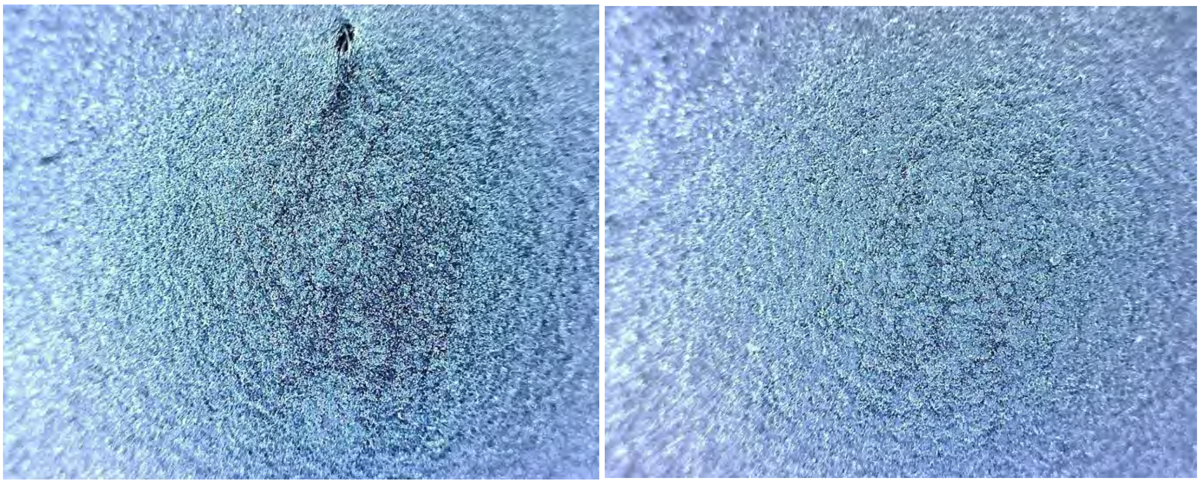
Coat.4 – surface after cleaning without biofouling (left) and with initial biofouling (right): Deep scratches visible.

Coat.5 – surface after cleaning without biofouling (left) and with initial biofouling (right): Deep scratches visible.

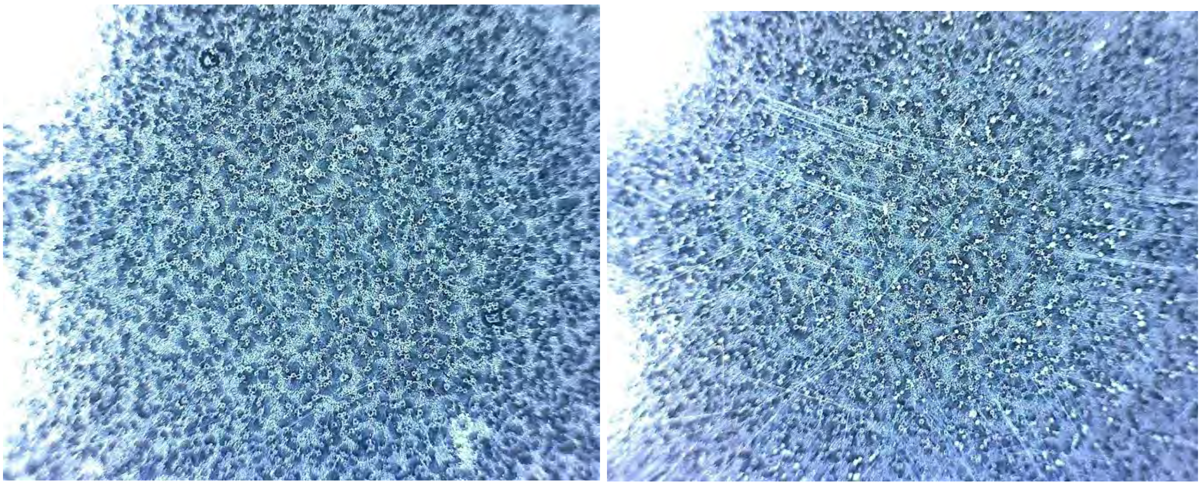


Coat.6 – surface after cleaning without biofouling (left) and with initial biofouling (right): Deep scratches visible.

Fig.15: Close-up pictures of the surfaces of test coatings Coat.4-6 after cleaning with extra soft brush for 10 s without biofouling (left) and with initial Biofouling (right).



Coat.7 – surface after cleaning without biofouling (left) and with initial biofouling (right): No scratches visible.



Coat.8 – surface after cleaning without biofouling (left) and with initial biofouling (right): Deep scratches visible.

Fig.16: Close-up pictures of the surfaces of test coatings Coat.7-8 after cleaning with extra soft brush for 10 s without biofouling (left) and with initial Biofouling (right).

4. Discussion

In its 2023 “Guidelines for the Control and Management of Ships' Biofouling to Minimize the Transfer of Invasive Aquatic Species”, *IMO (2023)*, the IMO did not rule out either reactive or proactive cleaning (grooming) of biocidal coatings. In 2025, it clarified its statements to the effect that cleaning on biocidal coatings should not ‘significantly increase dissolved biocides, particulate biocides, plastics or microplastics near the cleaning unit, relative to ambient levels’ and that no particles larger than 10 µm should be released into the environment, *IMO (2025)*. Cleaning without collecting the resulting particles and wastewater should only be carried out in the biofilm stage when there is no macrofouling present. Exceptions are locally operating ships with biocide-free hard coatings. In these cases, macrofouling should also be able to be cleaned off without collection. If cleaning is carried out on coatings containing biocides, the biocides contained therein are released. Washing water samples have shown concentrations of up to 365 µg/l copper and even 3820 µg/l zinc, *Soon et al. (2021)*. In addition to the biocides contained in the coatings, microplastics are released during cleaning as well. *Soon et al. (2024)* assume an average microplastic release rate of 1.73 g/m^2 for ROVs. For divers, the figure is significantly higher at 19.29 g/m^2. In order to reduce emissions during cleaning, the ‘Guidance on In-Water Cleaning of Ship's Biofouling’, *IMO (2025),* calls on manufacturers to provide data on the resistance of their coatings. This should enable the cleaning method to be tailored to the coating. This data is largely determined by abrasion tests in the laboratory – at least for provisional approvals, *LR (2021), Daehne et al. (2023)*.

So, proactive cleaning/grooming on biocidal coatings might be a transitional solution to establish a word-wide cleaning infrastructure for vessels. When the network of cleaning stations is dense enough, or mobile tools have become established, a change to Cleaning-Resistant Coatings FRCs should take place.

However, the tests carried out have shown that the stress caused by cleaning is significantly higher even on coatings with light growth of hard fouling than on the same coating without fouling. *Foy (2021)* already described that fragments of hard fouling removed by brushing cause more damage to the coating than would be expected from the cleaning equipment.

Thinking of ships, although the fouling was categorised as biofilm, there will always be a tiny amount of macro fouling present, either sparsely scattered around the hull, in niche areas or in areas, where the coating has been damaged or worn off. Therefore, there will always be areas where wear and tear from cleaning is greater than expected. Although the effect may be very slight with a single cleaning, the additional wear adds up over the service life, especially with proactive cleaning at short intervals. The coating could then have been severely damaged or completely worn off in these areas before the planned service life. Furthermore, a coating made for grooming is most likely tailored to be cleaned by a less abrasive method, e.g. a medium-hard brush. The medium-hard brush itself is unlikely to cause any damage. But entrained hard, sharp fragments of calcareous organisms on the other hand might cause severe damage to the coating and increase wear. On top of that, rough surfaces are more attractive colonisation sites for fouling organisms, *Thouvenin et al. (2003)*, further decreasing the cleaning intervals. The new fouling organisms then in addition adhere stronger to the scratched surface, *Lin et al. (2025), Callow et al. (2002), Daehne (2012)*. Information about short-term damage to the coating can be obtained through tests like the one above. For this, coated panels are let to selectively overgrow with initial hard fouling. This is then cleaned in accordance with the specifications, after which the damage is assessed.

While there was no abrasion by treating the test coatings that have been only exposed to distilled water with the extra soft brush, some of these coatings showed distinct scratches and abrasion when cleaned with initial biofouling. Scratches obviously are not mainly caused by the bristles of the brushes but by detritus of the hard and sharp-edged shells of even very young barnacles. Additional effects by very young blue mussels are unlikely, but effects by small oysters, which can settle and grow also in 3-4 weeks might cause additional problems in cleaning effectivity, Fig.17.

The experience shows that depending on location and season sometimes very short grooming/proactive cleaning intervals are necessary to remove hard fouling in good time. *Ralston et al. (2022)* for example had decided to groom test panels weekly and have achieved good results concerning cleaning effectivity.

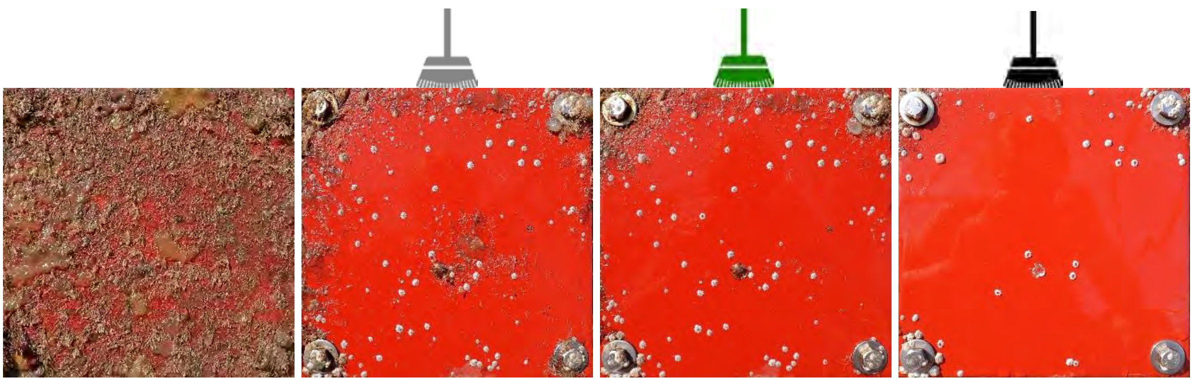


Fig.17: Coat.9 had a lot of soft fouling by ascidians and arborescent bryozoans, but also hard fouling by several Austrominius modestus and two Balanus improvisus and two small Pacific Oysters after an immersion period of 4 weeks. Extra soft and medium hard brush for 10 s could not remove them significantly, only the ultra stiff brush for 80 s removed most barnacles and destroyed one oyster.

The Taber Abraser still seems to be the best way to simulate years of wear and tear caused by abrasion in a short period of time. However, these tests have only been carried out in dry conditions so far. The coatings discussed here are designed for use in underwater environments. This is also where they will be exposed to cleaning stress. The results of the Taber tests carried out here suggest that the coatings behave differently when exposed to wear in water than when dry, resulting in a greater abrasion under wet conditions. Some of the increased abrasion may be caused by loose abrasive particles from the abrasive wheel, which have gotten back under the wheels and thus increased the abrasion. However, preliminary tests showed that this probably is not the only reason. During the tests, in which the water circulated, and the abrasion area was therefore rinsed, the abrasion was higher than in the tests with static water, where grinding sludge formed, whereby more free abrasive particles were drawn under the friction rollers.

One aspect that may also have contributed to the higher abrasion in the wet tests is water uptake. This involves water diffusing into the coatings and softening them, *Bratasyuk (2024)*. Although this effect should only affect the surface of hard underwater coatings, the softened surface would be continuously abraded, allowing water to reach the layers below and restarting the cycle.

Nevertheless, to avoid unpleasant surprises during use, wear tests for underwater coatings should be carried out under wet conditions.

5. Summary

Dr. Brill + Partner, at its Institute for Antifouling and Biocorrosion on the North Sea island Norderney, conducted comparative studies on the resistance of hard coatings by Taber abrasion under dry and wet conditions. Wet conditions simulate the real conditions at In-Water Cleaning much more realistically. The results so far showed that all test coatings had a higher abrasion at wet conditions. So, it is highly recommended to do Taber tests under wet conditions to avoid false positive results.

Additionally, simulated field tests with regular proactive brush cleaning have been carried out without biofouling and with initial biofouling. It became very clear that hard coatings, that have been considered as robust at cleaning without fouling, showed distinct abrasion in simulated field tests with initial biofouling even by soft brushes, when debris e.g. from destroyed shells of removed small barnacles scrub on the coating surface.

The experiences show that depending on location and season, sometimes very short grooming/proactive cleaning intervals are necessary to remove hard fouling in good time.

Surprisingly, Coat. 9, which had the lowest abrasion at the Taber test at dry as well as at wet conditions, showed a lot of scratches in the brush test. This could promote the re-settlement of biofouling after cleaning and shorten cleaning intervals, but obviously the coatings thickness and thus the service-life won´t be affected.

Overall, it became very clear that hard coatings, that have been considered as robust in dry abrasion tests in the lab, show distinct abrasion in wet abrasion tests in the lab as well as in simulated field tests with biofouling. It therefore seems appropriate to adapt the methods of the stress tests.

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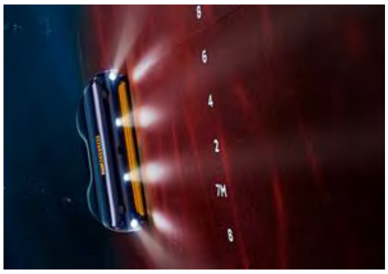
7th In-Port Inspection & Cleaning Conference (PortPIC)

Mülheim/Germany, 16.-17.9.2026





Topics: Aquatic Invasive Species / Diver operations in port / Next-generation antifouling technologies / Operator perspective on cleaning / Performance-based cleaning / Regulations & Guidelines / Robotic cleaning & inspection

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anytime	Optional "early warning" of interest to submit paper / participate
15.05.2026	First round of abstract selection (1/3 of available slots)
15.06.2026	Second round of abstract selection (remaining slots)
15.08.2026	Payment due for authors
15.08.2026	Final papers due

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