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Ship hull fouling by marine organisms: Environmental impact and removal methods

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THESIS

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Abstract

Biofouling refers to the accumulation of marine organisms on submerged surfaces, such as ship hulls, underwater structures, and marine equipment. These organisms include algae, barnacles, mussels, sponges, and various microorganisms. Biofouling occurs when these organisms settle and grow on surfaces in aquatic environments. The process begins with the settlement of microorganisms, such as bacteria and diatoms, on the surface. This initial colonization provides a substrate for larger organisms, such as algae and barnacles, to attach to. Over time, a complex community of organisms forms, leading to the formation of biofilms and macrofouling organisms. The environmental impact of ship hull fouling, caused by the accumulation of marine organisms on the hull surface, can be significant and multifaceted. Biofouling increases hydrodynamic drag, which leads to higher fuel consumption and greenhouse gas emissions. Ships must burn more fuel to maintain speed and efficiency, resulting in increased CO2 emissions and other pollutants released into the atmosphere. Various methods are used to prevent or control biofouling. These include the application of antifouling coatings on ship hulls and underwater structures, which release biocides or have surface properties that discourage organism attachment. Mechanical methods such as hull cleaning and the use of ultrasound ,brushes and ROV are also employed to remove fouling organisms.

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a. Definition

Marine fouling is the accumulation of various organisms such as algae, mussels, barnacles and crustaceans on submerged surfaces in marine environments. These organisms attach themselves to surfaces like pipes ,tanks and ships' hulls. Over time, the accumulation of fouling organisms can lead to the formation of biofilms and macrofouling communities. Fouling organisms can have various negative effects on submerged surfaces, including increased hydrodynamic drag, reduced fuel efficiency of vessels, corrosion of structures, interference with sensors and equipment, and ecological disruptions due to the transport of invasive species. Therefore, marine fouling is an important consideration in marine industries, shipping, and coastal infrastructure management, with efforts focused on prevention, mitigation, and control strategies to minimize its impacts.

Biofouling inspections are essential for ensuring the cleanliness of a ship's hull. Historically, the approach to biofouling inspections has been more reactive than proactive among ship superintendents and those responsible for management. Vessel operators generally conduct inspections solely in response to changes in performance indicators, such as a decline in speed or a rise in fuel consumption, which reflect variations in efficiency. This reactive strategy frequently results in heightened maintenance expenses, diminished fuel efficiency, and an increase in greenhouse gas (GHG) emissions.

A report published by the Global Industry Alliance for Marine Biosecurity (GIA) in 2020 indicated that inspections for biofouling on vessels generally take place only after a significant decline in speed, ranging from 5% to 100%, which signifies considerable fouling. This postponement leads to a notable decrease in operational efficiency and an increase in fuel consumption, attributed to the additional drag caused by biofouling. The detection of this 5% to 10% reduction can occur over a span of weeks, months, or even years, resulting in considerable financial costs and increased greenhouse gas emissions due to the excess fuel consumption.

Inspection methods

Biofouling inspections play a vital role in evaluating maintenance strategies. The predominant method employed is visual inspection, where divers or remotely operated vehicles (ROVs) examine the condition of the hull and detect initial indications of biofouling. Ultrasonic thickness measurements are employed to assess the condition of hull coatings and to detect any deterioration caused by biofouling. Furthermore, obtaining samples from the hull and underwater surfaces provides a means to examine the variety and abundance of organisms present.

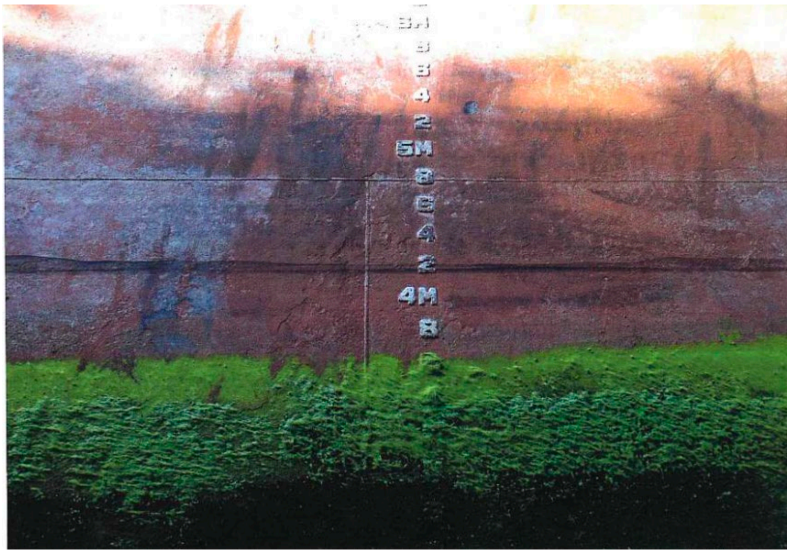
Routine inspections are advised to avert significant fouling that may affect operational efficiency. The interval between inspections may differ depending on various operational factors, including water temperature, salinity, and the nature of the routes navigated. Biofouling assessments typically employ particular criteria to evaluate the extent of fouling, including the degree of coverage, the species of organisms identified, and their influence on hull performance.

Inspection data is meticulously recorded and analyzed to track biofouling trends over time. This information is crucial for assessing performance and planning maintenance activities. Sophisticated software platforms exist that can integrate inspection data with environmental factors to provide predictive analytics. The results of inspections are compiled into reports that detail recommendations. In cases where substantial biofouling is identified, action plans may involve modifications to cleaning procedures in accordance with established protocols.

The growth of biofouling on a vessel's hull is greatly affected by its operational profile, which encompasses elements such as speed, frequency of voyages, duration of port stays, and the geographical areas in which the vessel operates. Practices such as slow steaming, prolonged inactivity, and operations in warmer waters can enhance and expedite the accumulation of biofouling.

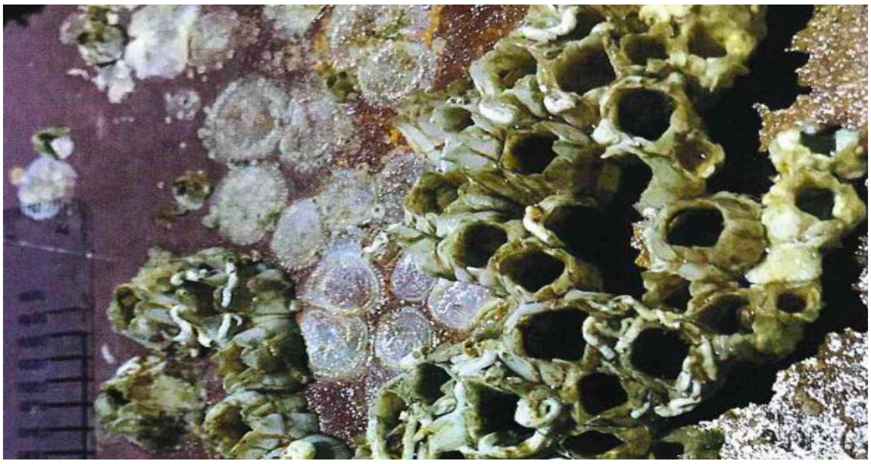
b. <u>Different types</u>

The diversity of fouling organisms is something we can all see when visiting the coast. The growth om rocky shores or other hard surfaces such as pillars below piers. The most seen type of algae is the green alga which is also called grass simply because the surface covered in these has the appearance of a grass lawn. All plant life needs light to grow and this is explains why it is limited to the vertical sides of ships and not found on the darker flat bottom. Fouling can be divided into different categories. First they are categorized by size of the fully developed organism, giving the division between microfouling and macrofouling. Microfouling consists of a complex of bacteria, single celled plants and microscopic organisms. Macrofouling can first be divided into plants and animals ,with the latter being further divided into soft and hard fouling. Common to all hard fouling is the presence of a shell protecting the organism within, usually made of calcium carbonate. Animal fouling is much more diverse than the algae with many different organisms being represented. Most of them are filter feeders and feed on the plankton in the seawater. This means that they will also eat the planktonic stages of their own and other fouling organisms. The adult forms of these organisms have the role of producing the next generation by laying eggs while developing larvae colonize new surfaces and spread the species short distances by following the ocean currents. By attaching to ships, the adult forms have also taken on the role of dispersal and this has led to concern about their introduction to new geographic areas as an alien species, which is against the IMO regulations and discussed in next unit.



Picture 1- In docking seaweed and algae

Among the marine animals barnacles, hard animal fouling, are predominant. Barnacles typically prefer nutrient rich coastal shorelines but can also occur as far as 20 to 30 miles offshore as well as deep in the oceans. There are several different species of barnacles which may be found attached to such a variety of surfaces including driftwood and floating garbage. Also common are mussels, they have hard shell but are only weakly attached by threads called byssus which makes them mobile compared to barnacles which attaches permanently to a surface. If a vessel is fouled with mussels it is highly likely that it has been stationary for a long period prior to docking. (Karyani et al., 2023).



Picture 2- Barnacles

Soft animal fouling is the type that lacks hard shell and they are typically classed as either a bryoza or a Hydroid which look similar but are in fact totally different types. Bryozoa have forms that are very soft and are often confused with algae as they grow as a network over a surface and send up many flexible strands that resemble brown algae. Hydroid is another species of soft animal fouling which is closely related to jellyfish and sea anemones. These can also resemble brown algae, or the upright types of bryozoan, but the are larger species called tubularian which can sometimes be found in larger areas of the flat bott om of ships.

Picture 3 - Bryozoa

They are few types of plant fouling that can be found all over the world. Two main types of seaweed are commonly found on ships. Ulva is perhaps the most common alga seen on ship hulls, it reproduces by releasing millions of spores that travel short distances to find new surfaces to colonise. These have adapted to higher levels of light and are found between the waterline and a few meters deep depending on the clarity of the water. Ectocarpus, short stunned black or brown growths require less light than entermopha and may therefore be found considerably deeper below the waterline.

The common feature to all fouling organisms is that they attach to surfaces. To achieve this, they have stages in their life cycle that are specialized for this. When it comes to microfouling this is less complex and both bacteria and single celled algae can detach from one surface, float around and attach to new surfaces.

c. Fouling timeline

The timeline is entirely dependent on the type of fouling present however it provides a useful overview. From the moment an object enters the sea, a conditioning film adheres to the surface which acts like a primer and lays the foundation for subsequent fouling. From there a layer of biofilm starts to develop which is where fouling starts to become visible. Depending on conditions juvenile macrofouling may also begin to settle at the same time or in place of the biofilm. Over time these fouling types would mature, causing problems for a vessel.

d. <u>Environmental and operational factors affecting fouling intensity</u>

As different types of fouling, also relevant are the factors that affect the intensity of fouling which is the rate or probability of fouling ooccurring towards a substrate. Relating this toward the marine industry and ship operations, these are environmental and ooperational factors that can increase the intensity and therefore the probability of fouling intensity a vessel out at sea. Knowing these factors would help ship operators to understand the fouling intensity a vessel is exposed to in its area of voyage and help plan for it. Some of the most important environmental factors are distance from shore ,water depth, water temperature ,sunlight intensity and duration salinity of water. As with any living organism can grow and multiply. With ooptimal conditions met , a population explosion can occur. When this happens the probability and severity of it occurring towards a vessel would increase.

Table 1

Environmental factors	Low intensity	High intensity	Explanation
Distance from shore	Deep sea	Coastal	In coastal waters, near to land there is an abundance of nutrients and minerals originating from inland. These minerals travel to the coast via estuaries from rivers and streams and high concentration occurs in coastal areas.
Water depth	Deep sea	Coastal	In shallow water it is warmer due to temperature from water surface affected by sunlight. In deep sea where it is colder and dark the

			propagation rate of microorganisms slows down.
Water temperature	Low temperature	High temperature	Warm waters have more potential energy which helps biological growth and reproduction of fouling organisms.
Sunlight intensity	Weak light intensity	Strong light intensity	Sunlight is a requirement for microflora such as algae to undergo photosynthesis.
Duration of sunlight	Shorter periods	Longer periods	The longer time a plant can photosynthesize the higher the rate of multiplication it will experience.
Salinity of water	Fresh water	Brackish water to salt water	Brackish water nearer to coastal tends to be higher in nutrients due to proximity to land.

On the other hand ,activity and speed of vessel are operational factors that they can relate more to the situation a substrate or in this case a vessel is deployed an taking into consideration the environmental factors it is being exposed to. When a ship operates in a location where environmental conditions are optimal for fouling to occur, the probability of fouling is high. How the vessel is operated can reduce or increase the chances of fouling further.

Table 2

Environmental factors	Low intensity	High intensity	Explanation
Voyage activity of vessel	High activity	Low activity	Ships which are on constant voyages reduces the intensity of fouling my movement itself. It is difficult for fouling organisms to attach into a moving object as compared to a stationary one. Ships which move 70% of the time are less likely to foul compared to a ship which only moves 50% of the time.
Speed of vessel	High speed	Low speed	Even if a ship has high activity, if the activity is based on slow speeds, it is still highly possible for fouling to occur. Ships moving below 5 knots are subjected to higher fouling intensity while ships moving at 28 knots are exposed to almost no fouling intensity whilst moving.

Biofouling inspection methods

Visual inspections represent the most commonly utilized approach. This process typically involves the deployment of divers or remotely operated vehicles (ROVs) to assess the condition of the hull visually and to detect early signs of biofouling. Ultrasonic thickness measurements are employed to evaluate the integrity of hull coatings and to identify any degradation caused by biofouling. Sampling entails the collection of specimens from the hull and submerged surfaces for the analysis of the types and quantities of organisms present. The frequency of these inspections may fluctuate based on operational conditions, such as water temperature, salinity, and specific navigational routes. It is advisable to conduct regular inspections to prevent significant fouling that could negatively impact performance. The information obtained from these inspections is documented and analyzed to track biofouling trends over time. The findings and recommendations from these inspections are compiled into comprehensive reports. Should significant biofouling be detected, action plans may include enhanced cleaning procedures or necessary modifications.

Biofouling detection using acoustic sensors

At present, the majority of underwater inspections are conducted by divers utilizing visual or sonar cameras. Nevertheless, visual technology presents certain constraints in the examination of vessels. The primary limitation is that this approach is only viable in conditions of adequate water visibility. Furthermore, the visual identification of biofouling types does not facilitate accurate classification, particularly in determining the precise thickness levels.

A pioneering solution for underwater inspection using autonomous underwater vehicles is to collect high-resolution data in low-visibility waters (Subdron).

The technology includes underwater localization to facilitate safe navigation in confined spaces, along with 3D scanning functionalities and biofouling detection utilizing acoustic sensors. Furthermore, it incorporates data processing to create a 3D asset model and to automatically identify potential problems. This solution provides considerable benefits to port authorities by enhancing the oversight of underwater assets and digitizing infrastructure, while also offering accurate hull assessments and biofouling maps to ship owners. Subdron is pioneering a groundbreaking autonomous underwater inspection solution that effectively navigates confined spaces while gathering accurate data. The proposed solution integrates an underwater navigation algorithm with a data cloud that autonomously reconstructs the surveyed area in three dimensions, facilitating the detection of biofouling. Additionally, it features a user interface that enables end users to visualize and interact with the data. These services enhance monitoring efficiency and decrease expenses, thereby providing superior hull monitoring within a reduced timeframe and at a more economical cost.

The data can be retrieved via Wi-Fi from the surface once the vehicle has landed, after which it is transmitted to the cloud for further processing. The cloud infrastructure systematically compiles and organizes the imaging data into three-dimensional point clouds by employing a range of machine learning algorithms. This functionality allows the system to produce 3D reconstructions of the inspected structure with a precision of one centimeter.

A variety of machine learning algorithms have been created to independently identify and emphasize potential irregularities, including deformations, voids, foreign objects, and biofouling, as well as to evaluate thickness measurements. Furthermore, these algorithms are capable of detecting changes in data collected from the inspection of the same object across different time periods.

- **Hull:** The ship's hull, constructed of heavy-gauge steel, is designed to withstand the rigors of ocean voyages, the pounding of waves, and the immense weight of its cargo. The ship's hull is not just a passive shell; it's a dynamic element that directly affects its performance, safety, and longevity. The hull's shape is carefully designed to optimize hydrodynamic performance. This means minimizing drag, maximizing efficiency, and ensuring stability in various sea states. The hull's form can include features like a bulbous bow (which reduces wave resistance), a tumblehome (a narrowing of the hull above the waterline for better stability), and a variety of appendages for added control. Hull parts are the following

1. **Starboard:** refers to the right side of a ship, when facing forward**.**
2. **Port side:** refers to the left side of the ship

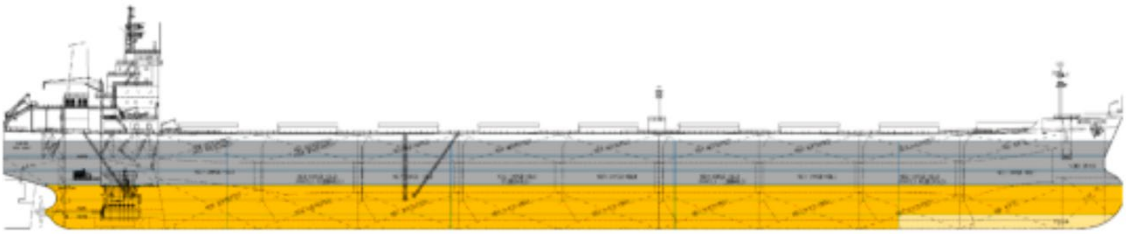
The terms "port" and "starboard" are nautical terms that have been used for centuries. They are important for navigation, communication, and safety on board ships.

3. **Flat bottom:** The bottom of the hull is relatively flat, with minimal curvature. This contrasts with traditional ship hulls that have a rounded, V-shaped bottom.

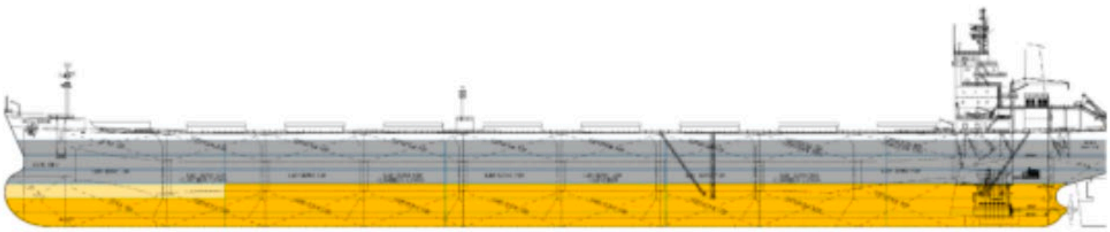
Fouling overview

- : Not inspected
- : No fouling
- : Light fouling
- : Medium fouling
- : Heavy fouling

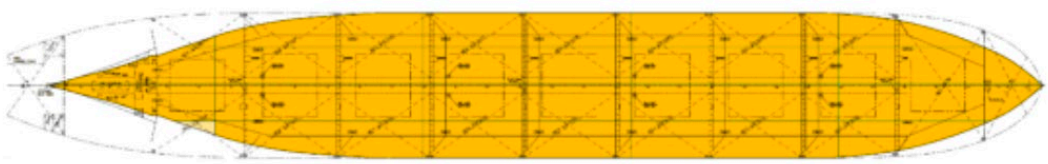
Starboard:



Port side:



Flat bottom:



- **Dimensions:** Bulk carriers vary in size, but they are generally long, wide, and deep, with a draft that allows them to navigate even the deepest channels. Their towering bulk is a sight to behold, dwarfing smaller vessels.
- **Holds:** The ship's heart lies in its cargo holds. These massive, open spaces, lined with steel, are designed to carry vast quantities of bulk materials – from grains and ores to coal and fertilizers.
- **Ship appendices** are additional structures attached to the hull that serve a variety of purposes, enhancing performance, stability, and maneuverability. Appendices play a critical role in the overall performance and safety of a ship. They contribute to stability, maneuverability, efficiency, and emergency preparedness. Understanding their function is essential for appreciating the complexities of naval architecture and the ongoing innovations in ship design.

Stability & Maneuverability:

- **Bilge Keels**: These vertical fins extending from the hull below the waterline act like stabilizers, reducing rolling motion and improving stability in rough seas.
- **Stern Skegs**: These vertical plates attached to the stern (rear) of the hull provide additional support and help to direct water flow for better steering.
- **Rudder**: While technically part of the steering system, the rudder is often considered an appendix. It's a large, movable flap that directs water flow, allowing the ship to turn.
- **Fin Stabilizers**: These retractable fins, often found on larger vessels, can be extended into the water to dampen rolling motion, improving passenger comfort and cargo stability.

Built for Efficiency:

- **Engine:** A powerful diesel engine, often exceeding 10,000 horsepower, drives the ship, propelling it across the world's oceans.
- **Fuel Consumption:** Bulk carriers, due to their size and the immense loads they carry, are known for their high fuel consumption. This has led to innovations in engine design and hull optimization to improve efficiency.
- **Propeller:** A ship's propeller is the key of the propulsion system, responsible for converting engine power into forward movement. It's essentially a rotating blade or set of blades that pushes water backward, creating thrust that propels the ship forward. Removing fouling from the blades is important for ship’s efficiency.
- **Crew:** A relatively small crew of highly skilled professionals navigates, operates, and maintains the ship, ensuring its safe passage and the delivery of its precious cargo.

Regulation has been part and parcel of antifouling coatings and has been driven by regulating bodies like IMO and local bodies like European Commissions.

EU-European Union monitoring, reporting and verification

What this regulation aims to achieve is the reduction of carbon emissions. Based on the 2nd IMO GHG study on emissions, it is noted that with use of proper technology, the potential for reduction of carbon emissions from the shipping sector is high. The strategy that EU have adopted consists of 3 consecutive steps. Firstly, monitoring reporting and verification of CO_2 emissions from large ships using EU ports. Greenhouse gas reduction targets for the maritime transport sector and further measures, including market-based measures, in medium to long term.

Main obligations can be summarized as followed

- MRV companies shall submit to an accredited MRV shipping verifier a monitoring plan using a template corresponding to the model in Annex I of Implementing Regulation (EU) 2016/1927.
- From 2018, MRV companies shall monitor for each of their ships CO_2 emissions, fuel consumption and other parameters, such as distance travelled, time at sea and cargo carried on a per voyage basis, so as to gather annual data into an Emissions report submitted to an accredited MRV shipping verifier

Emission Control Areas or ECA

ECAs are areas where regulations are being in placed to limit the amount of air pollutants emitted by ships and are regulated by IMO MARPOL Annex IV.

MARPOL Annex VI, first adopted in 1997, limits the main air pollutants contained in ships exhaust gas, including Sulphur oxides (SOx) and nitrous oxides(NOx), and prohibits deliberate emissions of ozone depleting substances (ODS). MARPOL Annex VI also regulates shipboard incineration, and the emissions of volatile organic compounds (VOCs) from tankers.

ECAs are areas where there is requirement to use fuel containing no more than 0.1% Sulphur unless exhaust scrubbers are used. There are several ECAs currently in force and numerous methods to comply with the regulation. One of the more popular options is the use of 0.1% Sulphur fuel oil. This option is approximately double the price of BW380 fuel which is widely used in non ECAs. As ECAs should lead to increased focus on hull performance, a clean hull will require less fuel consumption.

Biocidal Product Regulation or BRP

The Biocidal Product Regulation (BRP, Regulation (EU) 528/2012) concerns the placing on the market and use of biocidal products, which are used to protect humans, animals, materials or articles against harmful organisms, like pests or bacteria, by the action of the active substances contained in the biocidal product.

With regards to this, it is important to note that all paint makers would be affected in terms of use of biocidal ingredients in their antifouling coatings. BPR is a program which aims to unify, and control biocide use in the EU. Some biocides which have been banned include Irgarol and Diurion.

Energy Efficiency Existing Ship Index (EEXI) & Carbon Intensity Indicator (CII)

Since 2015, all new ships have been required to meet certain efficiency standards under the IMO’s Energy Efficiency Design Index (EEDI) regulations. At the IMO’s Marine Environmental Committee (MEPC 76) meeting in 2021, a decision was taken to extend this concept to existing ships not subject to EEDI rules. The new measure called called Energy Efficiency Existing Ship Index (EEXI) would require affected ships to meet similar requirements that could involve retrofitting energy saving devices, derating engines or adopting other energy saving measures.

At the same MEPC meeting it has also been agreed to implement an annual operational carbon intensity indicator (CII) and CII rating. This would be an extension of the MRV rules where ships would be obligated to achieve a C rating, and where performance falling below this standard, to take corrective action.

The environmental consequences of the global shipping fleet have garnered significant attention, with estimated carbon dioxide emissions representing approximately 3 percent of worldwide emissions. A study conducted by the International Maritime Organization (IMO) indicates that, without regulation, these emissions could increase by 150 to 250 percent by the year 2050. In response to this challenge, the IMO's Marine Environmental Protection Committee, during MEPC 62, has established a set of mandatory energy efficiency measures, known as the Energy Efficiency Design Index (EEDI), aimed at reducing greenhouse gas emissions from vessels.

Biofouling on a ship's hull can result in transmigration of invasive species into a local marine environment and its growth creates a higher consumption of fuel and eventually more GHG emissions into the atmosphere.

a. Environmental impacts from fouling

Many studies have been done and extensively considered in IMO (International Maritime Organization) on the impacts of biofouling. This has led to many regulations in the shipping community, but the basis of this impact is divided on twoo topics. One of which is the transfer of foreign invasive species from one location to another contributed by biofouling on ships and another is GHG (greenhouse gas) emissions from increased fuel consumption resulting from hull deterioration caused by biofouling both of which have a serious impact on the environment.

b. Transmigration of invasive species

Extensive research has been conducted to document the movement of marine species and its implications for local marine ecosystems. The introduction of harmful aquatic organisms and pathogens through biofouling can have significant repercussions for the environment, society, and various industries, as well as incur ongoing costs related to their management or eradication efforts. Notable high-impact species that have been introduced via biofouling include the Asian green mussel (Perna viridis) in the Caribbean, the clubbed tunicate (Styela clava) and sea vase (Ciona intestinalis) in Canada, the invasive alga (Hypnea musciformis) in Hawaii, and the black striped mussel (Mytilopsis sallei) in Darwin Harbour, Australia.

Biofouling is believed to contribute significantly to the ecological consequences associated with invasive species, which are intricate and arise from modifications to local biodiversity and/or changes in ecological processes induced by these species. Although the initial effects may be subtle and not easily noticeable, the severity of these impacts tends to escalate as the population grows over time. Such effects may encompass competition with native species for resources such as space and food, predation on native species, alteration of habitats for other species, displacement of native species, a reduction in native biodiversity, and in some cases, even local extinctions, along with changes in environmental conditions, such as diminished water clarity.

Biofouling on vessels is identified as a significant contributor to the global coastal transfer of Non-Indigenous Species, accounting for approximately 56 to 69 percent. The relatively brief duration of ship voyages enables marine organisms to be transported rapidly, allowing them to survive and remain viable upon reaching new environments. Ports that are highly interconnected attract ships from various geographical regions, resulting in a potentially high influx of both the number and diversity of invasive species. These ports, which serve as entry points for potential invaders, are typically characterized by hard substrates, sheltered conditions, and elevated levels of pollution.

The enhancement of shipping connectivity intensifies the risk of introducing potential pest species into ecosystems that are already under stress from significant human activities and climate change. In these compromised ecosystems, the establishment of non-native species is made easier, as the decline in biodiversity increases their vulnerability to invasions. Species originating from the departure port are more likely to flourish and become established in an arrival port that exhibits comparable salinity and temperature conditions.

Marine species can be introduced to new environments through shipping in three main ways: through ballast water, adhering to the hull, or associated with specific hull structures, as indicated by Schimanski et al. (2017). In ballast water, species are transported in their larval forms as free-swimming plankton. The Ballast Water Management Convention established by the International Maritime Organization, which will be applicable to existing vessels starting in

September 2024, seeks to mitigate the transfer of these planktonic organisms. Furthermore, in addition to biofouling on flat hull surfaces, specialized structures or designated areas known as niche areas of ships are acknowledged as critical points for the transfer of aquatic organisms.

Without addressing biofouling of ships as a sector, the considerable efforts made internationally to manage ballast water will only go part way to minimizing translocations of harmful aquatic organisms and pathogens

Research is currently underway to explore the potential for tracking invasive species through shipping data. To effectively trace the origins of invasion events, a comprehensive understanding of the particular species in question, along with the shipping vectors involved, is essential. The information required for each species includes not only its distribution range and initial sightings but also various biological traits such as tolerance to temperature and salinity, reproductive behaviors, dispersal mechanisms, and habitat preferences. Furthermore, to identify vessels, ports, and routes that are at high risk, it is essential to examine the attributes of the vessels along with their shipping behaviors. Ecological habitats of connected ports as well as shipping patterns between ports in infected areas are also investigated.

c. Hydrodynamic impact

As mentioned in previous unit, biofouling on the underwater hull of a vessel leads to increased fuel consumption and thereby to increased GHG emissions. The fuel consumption increases as the engine requires more fuel to deliver additional power to propel the vessel once fouling attaches to the underwater hull. The relation between the characteristics of a vessel hull including its underwater surface and the demand for propulsion power and consequently fuel consumption can be described in terms of hydrodynamics.

Hydrodynamics is a branch of physics that address the motion of fluids and the forces acting on solid bodies immersed in fluids and motion relative to them. With regards to a vessel it is a study of how a vessel’s hull behaves in water and the study of the resistance it undergoes while moving through water. When a vessel moves through water, it needs to overcome resistance from the water. The two dominating types of resistance are wave making-breaking and frictional resistance. The wave making-breaking resistance depends on the shape of the vessel hull (breadth, shape of bulbous bow etc) and is essentially given once the hull is designed and model testing is conducted. The amount of frictional resistance a vessel experiences is a function of the size of the wetted underwater area. As such it is dependent of the vessel design and also on the condition of the surface, especially its roughness. (Liu et al., 2023)

The smaller these resistance components are, the better the hydrodynamic efficiency of a ship. By working on the design of the hull shape, it is possible to reduce the wave-making resistance. On the top of having a good hull design, the surface condition of a vessel is influential. With higher fouling extent or a corroded and rough hull, the frictional resistance of the ship is higher, contributing to a lower hydrodynamic efficiency of a vessel by controlling the roughness of the hull initially and contributed by biofouling.

Depending on the type of ship with their typical hull shapes and typical speed ranges the relative contribution of the different resistance components to the total resistance varies. For bulkers and tankers, the typical frictional resistance is 70-90% of the total resistance. Managing the surface character of the underwater area is important for securing good hydrodynamic efficiency.

For deeper analysis of frictional resistance, there is a key concept to comprehend, the boundary layer. When a vessel surface is moving through water, water will interact with the surface. A very thin first layer of water will form on the surface that is essentially stationary on the hull surface. This first layer will interact with the next layer of the water and this in turn with the next layer of the water and this in turn with the next and so forth. The first layer will have the same speed as the vessel, the next layer will be slightly slower, and the speed of these water layers will decrease moving outwards from the surface until the water is not accelerated anymore. What essentially happens is that the vessel drags along a layer of water because of the interaction of the water layers with each other and with the surface. This layer is called the boundary layer. The thickness of the boundary layer is accelerated to only 1% of the speed of the hull.

If a vessel wants to minimize frictional resistance and thereby increase hydrodynamic efficiency, the vessel would have reduce the amount of energy lost to accelerate water in the boundary layer. Simply put, one aims at reducing the boundary layer thickness and the level of turbulence in the boundary layer for a given vessel and speed. The character of the hull surface determines the boundary layer structure, and management of the hull surface is thus key to minimize the boundary layer thickness and thereby the frictional resistance.

Damaged FRC (Fast rescue craft) increases the risk of biofouling growth as these damaged areas act as anchor points for growth. One apparent limitation of FRC is the expectation of slime growth. The reasons for this include the following. As covered in previous chapter a boundary layer exists where the water is not moving. As slime growth exists within this boundary layer, there is little hydrodynamic force being exerted onto it. As such FRCs are prone to having slime growth, which can cause an average speed loss of 3% which results in a drop of hydrodynamic efficiency of 9%.

This however can be alleviated by undertaking underwater cleaning during operation which will be discussed in an other chapter.

d. Surface roughness

Surface roughness has a significant role in determining the boundary layer characteristics and therefore frictional resistance. An increase in the roughness results in more turbulent flow that increases the thickness of the boundary layer that leads to an increased loss of energy from the vessel to the water. A hull that is fouled has increased surface roughness which can lead to increased demand for propulsion power, consequently increased fuel consumption ,emissions and impaired maneuverability.

Average Hull Roughness is an important measurement in a newbuilding yard or during drydocking, but it is even more important how it changes over time until the next maintenance. As mentioned above, the lower the initial roughness, the lower the frictional resistance overtime which will lead to lower speed loss. Elements to surface roughness that are difficult to change and manage are the structure and construction of the hull itself or roughness due to damage or deformation. If these factors cannot be controlled, then the roughness out of dock can be affected by the quality of the surface preparation, the coating application and the antifouling coating itself.

With good surface preparation coupled with good product application, very low levels of roughness can be achieved.

Surface character of the hull can be so important for the overall resistance. That happens because as the ship is moving through, water will pull water with the due to the chemical interactions (shear forces) between the hull and the water and interactions within the water itself (internal shear forces). The innermost water layer that is in direct contact with the hull will have the same speed as the hull itself, in hydrodynamics referred to no slip condition. This accelerated first layer of water will interact with the next. These interactions will continue until the velocity gradient disappears, as each layer will move a little slower than the previous one. The union of water layers affected by moving hull effectively increases the hull's mass, meaning that more power is needed to push the body through the water.

Hydrodynamic efficiency changes can be expressed in terms of speed loss. Measuring the speed loss over time in a standardized way is the core of the ISO 29030 standard which aims at "Measurement of Changes in Hull and Propeller Performance . " The speed loss concept mentioned here is to serve as a simplified guide into understanding biofouling effects in frictional resistance overtime. Shaft power provides a good representation of hull performance as it is not influenced by quality of fuel nor loss of effect through engine condition as it is measured based on propeller shaft torque and rpm.

e. Speed loss

At a given time and for given environmental and loading conditions ,the relation between the vessel speed and the propulsion power required would be described by a speed-power curve. When the vessel is newly delivered, this would be the speed trial curve. At a later point in time, but under comparable environmental and loading conditions the speed-power relation will be identical if the underwater area of the hull is unchanged. If however the hull surface deteriorates, and the frictional resistance increases the speed-power relation will be changed. For the same power the vessel would not achieve the same speed as before, it would have lost speed. If one measures this speed loss and shaft power overtime, one can thus identify the impact of changes in frictional resistance due to changes in the underwater hull surface character.

The goal of speed loss concept is to ultimately provide a platform to determine the efficacy of any solutions which is related to reduction of frictional resistance overtime, in other words control and reduction of biofouling causing this frictional resistance. The goal of any solution countering frictional resistance would be to get average speed loss over time.

Inspection plays a crucial role for maritime shipping companies, as regular assessments enable the identification and mitigation of biofouling on naval vessels. Biofouling contributes to increased drag on vessels, resulting in higher fuel consumption and subsequently affecting greenhouse gas emissions. According to estimates from the US maritime shipping industry, biofouling adds approximately €36 billion annually to shipping costs (Sofar Ocean, 2024). Furthermore, certain organisms associated with biofouling can become invasive species, potentially entering ecosystems via vessels. Effectively addressing biofouling is essential for decarbonizing the shipping sector, lowering expenses, and preventing the proliferation of invasive species, as noted by the IMO (2023). To accomplish this, ship operators must accurately assess the location and severity of biofouling accumulation to implement cost-effective and proactive cleaning strategies.

Underwater inspections are crucial not only for addressing biofouling issues but also for detecting damage to vital ship components, such as propellers, which can jeopardize operational efficiency and pose safety hazards. Problems such as leaking stern tubes, damaged thruster tunnels, blocked sea chest grids, weakened bilge keels, and hull fractures can lead to costly repairs and environmental damage if not identified promptly. It is essential for port authorities to carry out regular assessments of port infrastructure to determine the condition of various elements, ensure safety, and implement preventive strategies to extend the lifespan of the infrastructure. Recently, the deployment of underwater vehicles, including Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs), has become increasingly common to aid divers in performing underwater inspections, a subject that will be explored in the following chapter.

Hull cleaning in shipyards is a critical maintenance operation aimed at removing marine growth, fouling organisms, and other contaminants from the underwater surfaces of a ship's hull. This process is essential for maintaining the vessel's performance, fuel efficiency, and overall structural integrity. Hull cleaning in shipyards is a vital operation that contributes to the efficiency, safety, and longevity of maritime vessels. By employing effective cleaning methods and ensuring proper maintenance practices, shipyards can help ship operators maintain optimal performance and compliance with maritime regulations.

Hull efficiency plays a vital role in determining a vessel's overall performance and operational expenses. The presence of biofouling negatively impacts hull efficiency by elevating the surface roughness of the hull, which in turn raises hydrodynamic resistance. This heightened resistance necessitates greater engine power to sustain the same speed, consequently leading to increased fuel consumption and elevated greenhouse gas emissions.

Hull Cleaning Methods

Using divers or remotely operated vehicles (ROVs) equipped with tools like scrapers, brushes, and high-pressure water jets to remove fouling.

ROVs is a hull cleaning operation which utilizes a purpose-built underwater hull cleaning machine, designed around general parameters that are analyzed in next chapter.

During the process of underwater hull cleaning the divers are to focus on using the softest tool suitable for the area to be clean is selected. In case of soft fouling, this would be soft brushes and plastic in order to prevent any mechanical damage of the coatings. For harder fouling the use of steel scrapers and similar tools might be required, however are to be used in a manner that this results in as little damage to the hull coating as possible.

Brush cart types have interchangeable brushes and adjustable pressures which allow control of the operation. This equipment is often operated by a diver which may be an issue for some companies due to safety policies.

Picture 4 – Typical Brush cart

Picture 5 – Diver using brush cart

Ultrasonic Cleaning:

Utilizing high-frequency sound waves to dislodge fouling, particularly effective for removing barnacles and other hard growths. This method works by simultaneously using ultrasound energy pulses in various frequency ranges, creating a pattern of alternating positive and negative pressures. Ultrasonic vibrations generate extremely high accelerations that can damage the cellular structures of fouling organisms. A significant advantage of ultrasonic protection is its ability to provide biocide-free safeguarding for vessels. This technology has now been extensively implemented in specialized areas of ships, including sea chests, bow thrusters, heat exchangers, and propellers.

Hull cleaning during Drydock

Drydocking is a process where a ship is lifted out of the water and placed onto a dry dock, allowing for maintenance, repair, and inspection of the hull and other underwater components. It's a crucial part of ship maintenance that ensures the vessel's safety, seaworthiness, and longevity.

During that process, hull cleaning is crucial for paint maintenance and prevention of fouling. Shipyards have dedicated equipment for hull cleaning, including cleaning stations, high-pressure water systems, and lifting devices.

Chemical Cleaning:

Chemical hull cleaning involves the use of specialized cleaning agents to remove marine growth, fouling organisms, and other contaminants from a ship's hull. This method is often employed in conjunction with mechanical cleaning techniques or as a stand alone process, particularly when dealing with stubborn fouling that manual methods cannot effectively address.

Sandblasting:

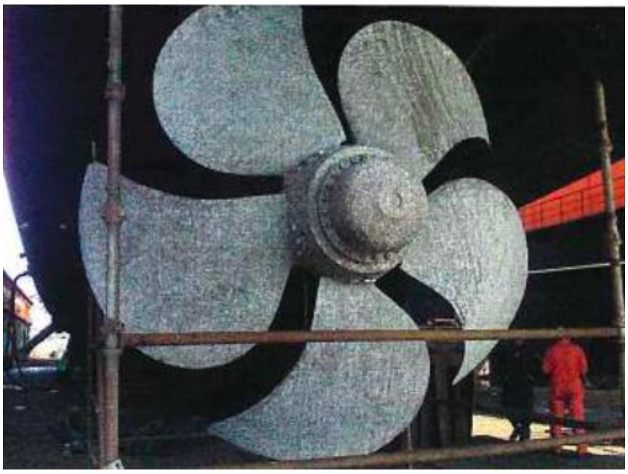
Sandblasting, also known as abrasive blasting employs various abrasive materials such as sand, aluminum oxide, glass beads, and steel grit. These abrasives are projected at high speeds onto surfaces using specialized equipment. The impact of the abrasive particles removes unwanted substances, leaving a clean and textured surface. Using abrasive materials like sand or glass beads to remove fouling, although this method can be harsh on the hull. Sandblasting ensures the surface is free from rust, old paint, and other impurities. This is vital for proper adhesion of coatings and paints, which protect the ship from corrosion and environmental factors.

Picture 6-Sandblasting during dry dock

Propeller Cleaning

Along the hull parts, fouling can also be found in propellers and the removal is also critical to good vessel performance. Propellers generally have no anti-fouling applied to them but they are some preventing measures.

Silicone-coated propellers are propellers with a thin layer of silicone applied to their surface. This silicone coating consists of a combination of biocides, fillers and pigments and acts as a barrier against marine growth. During the process of cleaning a coated propeller it is important to follow guidelines to prevent any significant coating loss.



Picture 7-Propeller before cleaning-polishing

Picture 8-Propeller after cleaning-polishing

<u>Cleaning silicone coating</u>

It is possible to successfully clean silicone coatings however they are more vulnerable to cleaning damage than biocidal antifouling because they are less starch resistant. To achieve the best results, the following key factors should be considered

- Use of softest brush possible because even a stiff nylon brush can cause damage
- If hard fouling such as barnacles are to be removed, ensure that they do not get trapped in the brush as this can damage the film
- Ensure that the brush cartwheels are soft and do not cause damage

If sufficient care is not taken it can lead to coating damages such as circular scratches leading to barnacle fouling.

<u>Fouling collection and Environmental Considerations</u>

Maintaining a smooth surface on a hull allows a vessel to navigate through water with reduced resistance. This decrease in resistance leads to lower fuel consumption, which in turn contributes to diminished emissions.

As the process of hull cleaning releases not only various types of biological fouling, which may be a threat to the local sea life and ocean habitat in the port, but also some of the paint coating in the form of pigments, binders and possibly biocides, many ports require the collection of this during hull cleaning activities. The removal step does not kill all the biofouling removed from the hull, a critical step is to capture the biofouling and treat it. This issue is why some countries and regions have introduced laws or regulations prohibiting foreign vessels from being cleaned in their ports or territorial seas .

Fouling collection can be accomplished by nets and screens ideal for larger fouling organisms like barnacles, vacuum systems for both small and large organisms but particularly effective for removing biofilm. Filtration and dislodgement processes are also an option using pipes and suction equipment.

Antifouling coatings

Control of biofouling has been a constant challenge throughout the history of shipbuilding and sea voyages. The way biofouling is controlled has been recorded with early primitive methods up until modern technologies being employed in current times. It is important to understand how these methods have evolved over time and the consequences of the methods used, leading to a diversification of antifouling technologies available in the market now.

A short glimpse on the history of antifouling coatings show a myriad of antifouling methods being employed to ensure smooth-running sailing of ships. The technology employed has been constantly evolving overtime. Biofouling control has been traditionally been using a substance that can stich to the hull surface of the ship with an active ingredient that deters these biofoulings. The concept has remained basically the same, but the ingredients employed have been employed with time and needs. Active substances have been employed like arsenic, mercury and tin-based products to currently Copper-based and more recently synthetic organic based substances with some current technologies not employing such ingredients altogether. Adhesive paste used to stick these toxic substances to the ship has also evolved from the use if pitch and tar to currently synthetic-based resin.

Organotin, especially Tributyltin (TBT) was introduced in the 60s and was an extremely potent biocide towards the control of biofouling. However, with further studies done in the 70s towards the effects of TBT on marine biology it was found to be extremely harmful towards the environment and was subsequently banned for the use in antifouling paints. The problem with TBT was its highly toxic nature that causes deformation towards marine life causing population decline and the length of time taken for TBT to completely decompose in seawater, particularly in areas of high sediments where TBT persisted. With regards to organotin it is important that ship owners only use antifouling which is in accordance with IMO Antifouling System Conference 26 Annex 1 which states the control and subsequently stoppage of use of organotin as a biocide. The ban of organotin compounds in antifouling coatings jump started developments on potential coatings previously considered before organotin compounds were introduced. Up until now most of these coatings have been based on a soluble binder system as the delivery system with the use of less harmful biocides working as the control substance toward biofouling. However, newer technologies like foul release coatings were also introduced as alternatives and will be discussed next.

Paint technology is a vast subject as it is related to antifouling coatings to give ship owners a brief understanding on the building blocks of an antifouling paint system.

Table 3

Components	Descriptions	Basic examples
Binders	Known as resin is the substance that holds all components together and where the overall performance of the coating is derived from. Can also be described as the delivery system for an antifouling paint.	Can be categorized into natural resins and synthetic polymers. There are many types of binders with examples including the following • Natural resins • Synthetic polymers used in antifouling including metal • Acrylates like zinc acrylate and copper acrylate and non-metal acrylates like silyl acrylate and silyl methacrylate. • Polydimethylsilxane (PDMS) is used as binder in all commercial FRCs
Biocides	Biocides are the active substance contained in the paint mixture that discourages the growth of biofouling. Biocides are an umbrella term which include substance like algicides (prevention of algae growth) and molluscicides (prevention of mollusk growth like barnacles).	In the chronology of antifouling there have been examples of using highly active metal or metalloid substance like mercury, arsenics, lead and until recently organotin which has all been banned. These compounds degrade slowly in the environment, hence pose a risk
Pigments	Pigments and extenders are fine particles that essentially gives the coating its color. Apart from providing color they affect other parameters of the paint like wetting and mechanical properties.	Some examples of pigments includes titanium dioxide which is a pure white pigment and iron oxide which provide dark toned colors like red and black. Both are processed from naturally occurring minerals.
Extenders	Extenders are fine particle substances similar to	Some examples of extenders include zinc oxide, calcium carbonate, calcium

	pigments. The properties of these vary considerably and they are used to adjust various properties including cost and performance.	magnesium carbonate and magnesium silicate. Zinc oxide is made via industrial process and the others are obtained from naturally occurring minerals.
Additives	Additives are special chemicals added in small quantities into the paint to achieve a desired property.	Some examples of additives are as follows. • Anti-settling agents which are used to prevent pigments and extenders from settling at the bottom of a can when paint is in storage. • Plasticizers used to make the paint film more flexible and less prone to cracking. • Thixotropic agents give better flow properties through a nozzle and promotes anti-sagging properties.
Solvent	Solvents with regards to antifouling coatings are generally liquid chemicals that disperses all the above material.	Examples of solvents used in antifouling coatings include aromatic hydrocarbon solvents made from petroleum distillates like xylene.

Biocidal antifouling

Biocidal antifouling coatings make up to approximately 90% of all coatings or fouling control measures used in the market. As described in the chronology of antifouling coatings, since the 18th century antifouling coatings have been used and further developed into what we called now modern antifouling systems.

Mechanism of biocidal antifouling: In simple terms, upon immersion into seawater, biocides contained in an antifouling coating will start dissolving into the surrounding environment. The way this leaching occurs is highly dependent on the characteristics of the binder system and seawater solubility of the biocide in question. As in basic paint technology there are many components that make up a paint system. With regards to biocidal antifouling, two of these components are extremely important in determining the efficacy of the antifouling. The first important component is the biocidal package. This essentially means the type of biocides used as the active ingredient against biofouling. There is typically one primary biocide employed with a second or third biocide, commonly referred to as co-biocide, added with each acting against a targeted biofouling type. The biocides employed must be effective against both flora (algae and sea vegetation) and fauna. The second important component is the binder technology of the coatings. The binder technology of an antifouling coating affects the way the biocide package is being delivered to act against the biofouling. If the concentration of a biocide is high in the paint film and low in seawater this will drive the biocide out of the paint film into the water. This is also why the consumption of biocide in the paint film is higher when the vessel is moving. As the freshly leached out biocides are quickly removed from the surface the high difference in concentration between the paint film and the seawater is maintained.

There are multitude of self-polishing coatings being offered in the market and ship owners are requested to consider the basic chemistry of the binder technology to understand the expectation of such coatings. From the various available antifouling the more common binder types can be separated into the following.

Table 4

Binder type	Examples	Reaction to water	Nature
Silyl (organic acrylate)	Silyl acrylate Silyl Methacrylate	Chemical hydrolysis	Hydrophobic Repels water
Metal Acrylate	Zinc Acrylate Copper Acrylate	Ion exchange	Hydrophilic High water uptake
Gum Rosin	Gum Rosin	Ion exchange	Hydrophilic High water uptake
Hybrids or Mixtures	Mixture of Rosin and Acrylates Copolymers of Silyl and Metal Acrylate	Mixture of reaction of the above Some term as partial hydrolysis	Partial hydrophilic/hydrophobic depending on the content

Silyl acrylate are non-metal acrylates which are hydrophobic in nature. The chemistry of silyl acrylates allows for the silyl ester to react with seawater, a reaction in which the silyl group is cleaved off. This means that reaction with seawater only takes place at surface of the binder. The molecule reacts (hydrolysis) and is transformed from water insoluble to water soluble components. Its characteristics include generally a thin leached layer with highly predictable polishing rate. The chemical temperature dependable reaction makes this technology highly predictable and enable paint thickness to be tailor made based on the expected seawater temperature for the trade in question.

Metal acrylate typically of copper or zinc are acrylates which are hydrophilic in nature. Similar to silyl acrylate, it also dissolves in seawater overtime. However, the reaction is like how soap (which also contains a metal ion) would dissolve in fresh water. Being hydrophilic in nature means that this binder absorbs water readily. With this high uptake of water molecules, the binder generally dissolves throughout the paint film releasing biocide. However due to this, the characteristics include a thicker leached layer which is unpredictable in polishing rate.

Unlike silyl and metal acrylates which are synthesized, **gum rosin** is a natural product made from secretion from trees mainly coniferous trees like pine. This has been a traditional resin used in antifouling products. Like metal acrylates, gum rosin is also hydrophilic in nature and would also readily absorb water molecules. However, being a natural product, the composition of resin acids in gum rosin is inconsistent. In some samples of gum rosin, it contains all the above structures which depending on the ratios has variable polishing rate. Amongst all the above binders, gum rosin would generally have the thickest leached layer. Gum rosin however, is also used as a secondary binder in silyl and metal acrylate systems to help control water absorption rate.

Currently most biocidal antifoulings are classed as self-polishing. This means in general, there is a depletion of the binder which is eroded. The difference between these coatings is the chemistry of polishing as well as how constant the polishing rate is, which is what makes the performance sufficiently predictable.

The silyl acrylate resins are typically based on the trialkyl silyl esters being a pendent side chain on the acrylic backbone. The silyl acrylate resin, or the silyl methacrylate resin, depending on the monomer used , is a non-charged polymer that undergoes a basic ester hydrolysis in natural seawater. In natural seawater, with a pH value of 8.1-8.3, hydroxyl ions (OH^-) will be present and attack the carbonyl carbon of the silyl ester functionality forming an intermediate orthoester. From this orthoester the deprotonated silanol is cleaved off and the resulting acid deprotonated due to the basic properties of natural seawater. The formed carboxylate is stabilized by metal ions present in seawater. Since the hydroxyl ions are required for the silyl acrylate to react and since the levels are rather constant in seawater this reaction is predictable.

Ion exchange technology is based on the ionic interaction between a metallic ion, usually a divalent ion (lacking two electrons and therefore having two plus charges) such as Cu^{2+} or Zn^{2+} and the carboxylate functionality present in the backbone of the acrylic resin as well as in the rosin structure itself. The ion exchange stands for the replacement of one material ion with another one – the exchange. The ions formed are stabilized by water molecules. In the presence of monovalent metal ions, the original divalent metal ion may be replaced by the monovalent as described in structure C. The original metal ion to form structure D. All these reactions will be competing to form the most thermodynamically stable complex, reducing the energy of the system and will be depending on the presence of other metal ions. The big variety of possible reactions make the technology less predictable. The formation of strong complexes with ions such as Calcium (Ca^{2+}) and Magnesium (Mg^{2+}) can form more stable complexes but it will however be more difficult to break affecting the solubility. The polarity of the resin system, based on the charges present, does often increase the water uptake of the resin. (Torres et al.,2021)

Types of biocides used in self-polishing coatings

Biocides are biologically active ingredients. They are designed to repel or kill the microscopic stages of fouling organisms, like algae spores and barnacle larvae. An antifouling needs protect against a wide variety of fouling organisms. In fact, more than 4000 different species of barnacles, mussels, tubeworms, algae, etc. have been identified. To provide protection against all these pests, a. typical antifouling paint consists of both a primary biocide and co-biocide so this combination will take care of both hard fouling + soft fouling organisms. Biocides have half-life, and the shorter this half-life is in the marine environment, the better. As an example, if the half-life is 1 hour the breakdown will be

100%-50% 1 hour

25% 2 hours

12.5% 3 hours

6.25% 4 hours

3.125% 5 hours

1.5625% 6 hours and so on

After 7 hours the compound will be broken down to less than 1 % of its original concentration.

Foul release coatings (FRC)

Foul release coatings are non-biocidal, silicone-based coatings which were introduced to the market as an alternative to biocidal self-polishing coatings. They currently make up 10% of commercially available biofouling control measures. Being non-biocidal, there is no active ingredient in the coatings to act against biofouling. Instead these coatings rely on a surface that makes it difficult for biofouling larva to latch onto. However, due to the coatings being non-biocidal, biofouling growth will still occur on these surfaces when a vessel is left idling for ling periods. In this case, physical motion of the vessel moving through water would cause the biofouling growth to detach by sheer friction against water, hence the term Foul Release Coatings. In some cases, however, if biofouling is totally left unchecked and these organisms have managed to dig deep roots into the coating, underwater cleaning would be required to remove it. The surface characteristics of foul-release coatings (FRCs) diminish the adhesive strength of biofouling, allowing for its detachment as the speed of the vessel increases. To ensure effective removal of biofouling, most manufacturers of marine coatings recommend that vessels maintain a minimum operational factor of at least 70% throughout the year, with an average speed of no less than 12 knots. FRCs are formulated using a silicone elastomer resin matrix, with some variations incorporating functionalized silicone oils and hydrogels to create a surface with very low energy. While the majority of FRCs do not contain biocides, there are certain products that include organic boosting biocides to enhance their performance in static conditions. Due to the inherent nature of elastomeric systems, they are susceptible to damage; however, they can effectively release adhered fouling with relatively gentle cleaning methods. It is advisable to avoid aggressive abrasive cleaning techniques, as these can harm the coatings. When applied correctly, the resulting surface exhibits a very low surface roughness, potentially being approximately 35% smoother than high-end self-polishing copolymers (SPCs) discussed in a next paragraph.

Mechanism of foul release coatings

There are two ways in which an FRC works. These two include the following mechanism, the reduce of the adhesion of biofouling. As mentioned, conventional FRCs does not contain biocides. As such instead of repelling biofouling from the surface like a biocidal antifouling would, biofouling growth would still be experienced on an FRC. How a biofouling organism attached itself to the surface is by use of glycoproteins and polysaccharides which are glue like substances. The concept of FRC then is to reduce the strength of adhesion of the bio-glue on its surface whereby these organisms would be removed by hydrodynamic shear or from friction against water when the vessel is moving.

Silicone is a hydrophobic material which means it does not promote absorption of water. This by itself does not work against promoting growth of biofouling and instead these are organisms which have higher affinity towards hydrophobic substrates as compared to others. The difference between the various FRC technology offered in the market is the additives that are added to the silicone binder. These additives as well as oil are typically amphiphilic in nature, which means that they partly attract water. Once added, these additives create a bivalent surface on the coating. Biofouling larvae, depending in its affinity towards a hydrophobic or hydrophilic surface, would firstly have to recognize and accept that the surface is suitable before latching on. The bivalent nature of FRCs however can confuse these larvae and hence reduce the attractiveness of the surface for settlement.

Alternatives to current antifoulings

Other alternative forms of antifouling exist, but their use is not as widespread as biocidal antifouling or foul release coatings. Here are some of the available forms, some of which are still in development.

Copper-free self-polishing coatings

With regards to biocidal antifouling, the major biocide is cuprous oxide. Although studies have shown that the toxicology of cuprous oxide is not detrimental to the environment, is still considered a toxic substance. In this aspect, some biopharmaceutical companies have developed synthetic drugs to act as an alternative to biocides. These drugs do not act as a killing agent like metal-based biocides but affect biofouling in other ways. For example, the drug metomidine was initially developed as an anesthetic used in veterinary science. Currently has been developed as biofouling control in such a way that when the drug meets a barnacle larvae , it stimulates a neuro-hormone or neuro-transmitter in the larvae nervous system causing the larvae to have a temporary involuntary movement. This temporary involuntary movement makes the larvae unable to latch onto the surface. The drug is effective at low dosage and as an organic substance, the rate of decomposition is extremely high making it highly applicable as biocide replacement. With advance in biopharmaceutical technology there could be more drugs in the future that can sufficiently act as biofouling repellent without posing any detrimental effects on marine life like bio-accumulation of toxic heavy metal substance. It could be possible that with such drugs that have high efficacy at low dosages newer copper free antifouling can be developed.

Biocidal FRC

Foul Release Coatings has some limitation with regards to slime growth which exists within the boundary layer when a vessel is moving. Also, as standard FRC are non-biocidal they do not actively repel biofouling growth when vessel is stagnant or idling for long periods of time. In this case, some paint makers are continuously developing variants of FRCs that contain biocides. The chemistry of silicone which cures to an elastomer means that the coating would become non-permeable. This means that the polymer structure unlike acrylates are non-porous resulting in close to non leaching of biocides if it was to be added. However, there are additives such as silicone oils that can be blended with silicone elastomer that can act as a mode of transport for biocidal leaching. Biocides, like copper pyrithione, are currently being used in such variants as an active component against the growth of slime.

Hard coatings

Some ships, especially ice going vessels, which do not experience high fouling intensity, usually go for hard coatings or ice class coatings. This would include high build epoxies and polyester based coatings, targeted to provide high mechanical strength against abrasion from ice while ensuring a smooth surface that has an extremely low coefficient of friction. As these coatings are non-biocidal, they are subjected of biofouling, but the tough nature of the coatings means it can withstand deterioration from regular underwater cleanings. HFRC, based on combinations of epoxypolysiloxane, graphene and hydrogel technology are relatively new in the commercial shipping sector and currently available through a limited number of suppliers.

They also exhibit a very smooth, low energy surface reducing the strength of the adhesive attachment of biofouling, however they are harder and less easily damaged and therefore can be cleaned with a more abrasive methods.

Copper rich epoxy

This technology is derived from adding metal dust into epoxy-based coatings which are traditionally used as primers. Similar to a zinc rich epoxy primer, where zinc dust is added to epoxy to provide self-healing properties for improved anticorrosion properties, copper dust is in this case added for its antifoulant properties. The copper dust within this copper rich epoxy paint will oxidize and turn into cuprous oxide that acts as a biocide. Epoxy however, being a cross-linked polymer or thermoset is insoluble, non-porous and non leaching. This means that only exposed copper dust on the surface will oxidize over time. The dust that gets encapsulated within the epoxy binder will not be reactive. Another issue with these form of paints is the risk of galvanic corrosion from pure copper dust that would require a primer coat to be applied before the application of a copper rich epoxy coating. Copper is a vital element found in nature, existing in both natural and anthropogenic forms, with no significant distinction between the two. Typically, the primary sources of copper entering the oceans include erosion or dissolution from bedrock and riverbeds, which is then transported by rivers. However, it is crucial to emphasize the environmental implications of anthropogenic copper. The release of biocides from antifouling coatings is subject to stringent regulations, and modeling calculations are employed to guarantee that such releases do not result in adverse environmental effects.

Ultra-sonic antifouling

This method of control involves using sonic frequency that can discourage growth of biofouling. It works by sending small sonic vibrations throughout the hull of the vessel or structure. These vibrations are in the ultrasonic frequency above human hearing. Whilst these pulses are small and cause no harm to fabric of the vessel or structure, they are disruptive to the bio film which in turn stops fouling. So far, these ultrasonic antifoulings have not been applied on large commercial vessels and limited to smaller ships and yachts. It is important to note that based on a study done on ultrasonic effects on biofouling, this system would only act as a deterrent on the early stage in a biofouling cycle but would not have any effects on a biofouling organism in its later stage. Ultrasound exposure effectively reduces cyprid settlement, yet metamorphosed barnacles grow normally. It is thus noted that this system could not sufficiently replace traditional antifouling bit can act as an auxiliary antifoulant system.

SPC coatings

Self polishing coatings consists of a combination of biocides to prevent fouling, fillers to make bulk of coating and designed to polish off over time and pigments to give the coating a color. SPCs are based on specialist acrylic resin technology and in most cases contain inorganic and organic boosting biocides. They are typically applied in two equally thick coats over the harder anti- corrosive as well as tie coats for 60-90 month docking cycles.

Typically, the tie coat will be a light creme/beige color, with the first coat of the self-polishing coating being brown and the topcoat being the normal red as seen on vessels. For vessels on 36 month docking cycles, only a single coat may be applied. Also, it often develop a thin, non-active, biocide free, leached layer on the surface, normally when vessels are idle for a period of time. This leached layer, when rubbed by hand, may be easily removed, and be seen as a light red discoloration of the water. During the process of hull cleaning, the removal of fouling is anticipated to also eliminate some of the previously mentioned leached layer, which in turn is expected to enhance the effectiveness of foul deterrence.

However, overly aggressive cleaning methods may lead to the excessive removal of active coatings, consequently diminishing the lifespan of the coating and resulting in premature fouling. It is imperative for divers to exercise caution to avoid the removal of the active SPC coating, as this would adversely affect the overall active life of the coating system. The SPC can be formulated to achieve varying degrees of hardness, thereby providing protection for vessels engaged in different levels of activity levels.

Required information in selection of antifouling

With regards to selection of antifouling, there are several pieces of information that a ship owner should seek to understand first before consulting a paint maker for antifouling specifications. This information will form the basis of the recommendation that the paint maker will provide to the ship owner and operator.

The following parameters are typical parameters that a ship owner should seek to find out. The reason for this is these parameters affects the types of antifouling coatings that would be recommended. Depending on the antifouling selected especially for self polishing coatings, these parameters would determine the thickness of paint requires to sufficiently protect the ship's hull for the required period. The thickness of the antifouling would ultimately affect the cost of the paint system to be specified for the vessel.

- Average seawater temperature (^{o}C)

Seawater temperature differs in different geographical regions. Typically, in areas near to the equator , the seawater temperature is higher than location further away from it. Seawater temperature influences the way certain antifouling coatings work, with any chemical reaction, with higher temperature the rate of reaction increases. With regards to self polishing coatings, in areas of higher seawater temperature, polishing would generally increase. It is however important to note that seawater temperature contributes to higher biofouling intensity. The antifouling coatings should perform at a reasonable polishing rate to cater for this temperature variation.

- Voyage factor (%)

This is an important parameter to consider as this influences the thickness of antifouling coatings especially self polishing coatings. A higher projected voyage factor would require more thickness to avoid over polishing. Over polishing means the coatings would have been deplete before the end of the duration increasing risk of biofouling to occur towards the end of the period.

This is the operational activity of the vessel. For example, if a vessel has total full steaming period of 75% of the time and 25% of the time in idle (on anchor/loading/discharging/shifting) in a year.

- Drydocking interval

This is the duration that an antifouling is required to last. This can be between a month to a 5-year period. Typically, the antifouling duration would be 30 months and 60 months period. Some eligible vessels under extended drydocking scheme would require a 90 months system. Per classification society requirement, a vessel is required to drydock every 60 months or 5 years. However, there are times when a vessel would require an intermediate survey in drydock due to various reasons. This intermediate survey would usually be between the 2nd and 3rd year. Hence, the duration of antifouling protection would be less than 60 months and typically at about 30 months.

- Average speed of vessel (knots)

This parameter describes the average speed in knots when the vessel is full steaming. Antifouling coatings such as self polishing coatings not only experience a chemical reaction with seawater but also physical reaction by means of frictional erosion. This differs with every technology. However, the speed of the vessel contributes to how fast a self polishing coating is depleted, hence influencing the thickness of the coating. With regards to other coatings like foul release coatings, this determines how effective the foul release mechanism would work.

- Nautical Miles Per month

Some paint makers have been recommending antifouling coatings based on this parameter. It is based on the distance by nautical mile which a vessel is expected to achieve in a month and then extrapolated for a year and for period required. This essentially is another way of looking at the vessel’s activity and usually compared to certain in house benchmark. However, specifying an antifouling coatings base on this parameter by itself may not be accurate as it does not take into consideration other parameters like seawater conditions.

- Longest Idle Days

The longest time a vessel would be idle, this include time spent on anchor, while at berth for loading or discharging or standby time while awaiting next cargo pick up. The reason this is important is that vessels are more susceptible to biofouling growth on hull when the vessel is idling. The polishing rate for self-polishing coatings would be reduce the efficacy of the biocidal protection if the vessel is on idle for too long. So, it is an important parameter to consider while finding out the limitation of an antifouling coating.

- Geographical Location of trading

Many vessels do not trade globally and only in specific areas. For example, ice-classed vessels usually operate in the Arctic or Baltic regions. Knowing the geographic region of a vessel's trading route is important as different region poses different challenges with regards to biofouling. For example, operating in the Arctic would pose very low fouling intensity. While areas like the West African coast or in Brazil would have higher fouling intensity.

Anti-fouling systems

- Biocidal Coatings as we saw in previous chapter are coatings that release biocides such as copper that prevent the attachment and growth of marine organisms.

- Non toxic FRCs, smooth coatings that don't prevent the organisms from settling but to adhere. When the ship moves , fouling is easily removed by the flow of water.

- Ultrasonic anti-fouling, sound waves disrupt the cellular structure of biofouling organisms and prevent them from attaching.

- Electrolytic or Cathodic Protection, using electrical current to prevent fouling an corrosion. Low level electrical currents discourage the attachment of marine organisms. In some systems, metal ions are released that create an environment unfriendly to biofouling. Often combined with biocidal paints or non-toxic coatings, particularly in combination with metal structures like propellers.

- Air bubble curtains are continuous streams of air bubbles that release along the ship’s hull. The bubbles create a barrier that disturbs water flow and prevents organisms from attaching to the hull and the used in dynamic environments or combined with other fouling control systems.
- Copper-Nickel Alloys are materials that naturally resist biofouling and corrosion. Copper in the alloy acts as a natural biocide, preventing the attachment of marine organisms. A great sustainable choice for specific components like propellers and seawater intakes, though they are expensive.

- In-water Hull cleaning systems (rotating brushes) are mechanical brushes or other cleaning devices are used to remove biofouling from the hull during operation or while the vessel is docked. Brushes regularly scrub the ship’s hull, removing fouling before it accumulates heavily. They are extensively discussed in the last chapter.

- UV-light systems are used to prevent biofouling by irradiating surfaces or water systems, killing organisms before they can attach. They it works is by damaging the DNA of microorganisms when a Thymine molecule is absorbing radiation λ=253,7nm by creating a covalent bond (dimer) between 2 nucleotide bases of thymine. This dimer is causing problems in the procreation of the molecule so it neutralized. (Εισαγωγή στις Διεργασίες καθαρισμού νερού και λυμάτων,2^{η} έκδοση, Κωνσταντίνος Β. Χρυσικόπουλος)

- Water Jet Systems are high pressure water jets that are used to blast away fouling organisms from the hull. The jets clean the surface by physically removing any growth. They are used for periodic maintenance when ships are in port or in dry dock.

Assessment of antifouling performance

In previous chapters, we have gained good insights into fouling an how it is influenced. Fouling can have a significant impact to speed, fuel consumption and consequently emissions, and it is therefore beneficial to monitor the performance of vessels allowing interested parties to measure the impact of fouling. There are several different ways to interpret the change in antifouling performance.

The simplest method to access hull conditionon is by visual assessment. It usually involves a diver inspecting the hull and providing photographs and videos of the hull and other areas of interest such as sea chests. This method of monitoring is available globally but with extremely variable levels of quality and price. Furthermore, it suffers from subjectivity making long term performance analysis difficult. Upon visual inspection of a vessel’s hull it is only possible to conclude on the presence or absence of fouling and damages. Further judgement on the severity of fouling can already be considered subjective. In addition, the diver will often be drawn to fouled areas and such may offer a wrong impression of the overall condition.

The best practice in this sense is to choose a dive company who is known for their high quality and safety standards. Additionally, the vessel manager should make a map of the hull and ,when reviewing the dive pictures and video, ensure all areas are visited during the inspection. This procedure ensures nothing is overlooked. Based on the information received from the diving report, the condition of the hull must then be assessed, and further actions taken if needed. It might be the case that the dive company suggests a full hull cleaning even if this is not needed.

For example, if light slime appears on the coating and it is the vessel operator who should take a decision on either cleaning the hull or not. Besides the fact that the visual inspection might be subjective, it can also provide information on the impact of hull surface topography on the vessel efficiency. All these aspects make it impossible to directly measure the cost and emission savings.

It should also be noted that a decision to clean the hull may also influence the remaining life time of the fouling protection offered by the system applied. A cleaning of a hull with light slime only can easily remove 50 μm of intact system, in additionon to the slime and the leached layer. These 50 μm can reduce the remaining lifetime of a polishing antifouling with up to as much as 1 year.

Another method is by fuel consumption monitoring. It’s a simple method for observing fuel consumption over time, however it can give incorrect or misleading results if one is attempting to analyze only the effects of biofouling.

Tracking of fuel consumption over time is an easy procedure that can be done by crew on board the vessel, nothing else but a flow meter is needed. It can also be done using a data logger receiving information from the flow meter that can send high frequency data of a vessel’s daily fuel consumption. The data can be collected by the minute or by the hour. Nevertheless, vessels can experience changes in fuel consumption that not related to changes in antifouling performance. For example, fuel consumption of a vessel will differ if changing draft or trim. The same will happen due to weather variations, currents, fuel quality differences or engine performance decrease. Therefore, by monitoring fuel consumption it is possible to conclude only on the overall vessel efficiency rather than isolating antifouling performance.

Third method includes ISO standard 19030- Measurement of changes in hull and propeller performance. The clear recommendation is to consult and determine whether it is workable and of interest for a case. ISO 1930 can be used, for instance, to crate contractual performance agreements between interested parties, for example owner and character or owner and paint supplier. The basic principle of ISO 19030 is to collect relevant data from on-board instruments, process it and then calculate the performance indicators. In the analysis method, per ISO 19030, changes in the operational and environmental conditions of a vessel are accounted for and thus allows to isolate the hull and propeller performance from the overall vessel efficiency. This means that ISO 19030 can be used to evaluate antifouling performance.

ISO 19030, as its title suggests, refers to the changes in ship specific hull and propeller performance is monitored by tracking the relationship between vessel speed through water and the required shaft power over time. For a given shaft power, vessel speed will decrease in time if the hull or the propeller gets fouled or damaged. The speed loss is the performance indicator used in ISO 19030.

One major difference between the ISO 19030 methodology and others previously mentioned is that although none of these analysis methods provide direct information on the impact of hull performance on the fuel cost, which is essential to determine return on investment, the former allows for very good approximations in this sense.

Location of use on a vessel

Antifouling coatings to be applied on different areas of a vessel's hull would also make a difference in the choice of the antifouling coatings. Typically, the areas where antifouling coatings are used would include the following.

- Boot Top area

This is the area between the waterline when a vessel is on ballast and when it tis fully laden. The entire area goes around the vessel. During laden voyages, this area is fully submerged and while on ballast voyage this area is exposed. As this area goes between being submerged and exposed, the biofouling intensity experienced is highly dependent on how long and frequent laden voyages are. The choice of antifouling coatings should sufficiently cater for this conditions.

- Vertical sides of side bottom

This is the area between ballast water line to the bilge keel. Ballast water line is a theoretical limit that helps ensure the safety and stability of a ship by regulating the amount of ballast water it can carry. It is not physically marked on the ship's hull. This area is typically fully submerged at all time.

The fouling intensity is the highest on the vertical sides as it always submerged and exposed to sunlight. All plant life needs light to grow and this is explains why it is limited to the vertical sides of ships and not found on the darker flat bottom. The choice of antifouling coatings should be the best possible to cater for this fouling intensity.

- Flat bottom

This is the area between bilge keel to bilge keel at the bottom of the vessel and is always fully submerged. Is a hull design where the bottom of the ship is relatively flat, unlike the rounded shape found in most vessels. While not as common as traditional rounded hulls. Fouling intensity is dependent on the size of the vessel.. For a supply tugboat, the fouling intensity of the flat bottom is the same as the vertical sides due to proximity the water surface and being exposed to sunlight. On large vessels the area in the flat bottom is so vast that a major portion of this area is in the dark most of the time. The choice of antifouling coatings for this area should include this consideration.

- Sea Chest

This area is located on the vertical sides as a water inlet to be used for drawing seawater for onboard operations. The chest is protected by grating to prevent large items from being drawn into the piping system. The sea chest experience high fouling intensity. Due to its box like structure, embedded in the side of the hull, the frictional erosion will be much lower inside the sea chest. It is therefore easier for fouling organisms to settle and grow inside the sea chest. If biofouling is not controlled in this area, it may lead to choking of pipes and pumps, or on grating from biofouling growth limiting water intake. The antifouling choice here should cater for this requirement.

- Rudder

The rudder is the location on a vessel that steers the vessels. It is usually subjected to high cavitation forces as it is typically located just after the propellers. Typically, the choice of antifouling for the rudder would be similar as the side bottom. However due to cavitation forces exerted from the propeller, this may lead to higher polishing rate on self-polishing coatings. The thickness of the coatings should be considered.

- Propeller

The propeller is part of the vessel that propels the vessel forward when power is exerted on its shaft by the engine. This is the location that experiences the highest form of cavitation forces. As such self polishing coatings may not be the best as the coatings would be the best as the coatings would be eroded extremely fast. Propellers may be coated with foul release coatings but the coatings will be subjected to high wear and tear especially on the edges. Generally, this area is usually not coated but polished on a regular basis by underwater divers.

Common Paint damages

One of the major concerns of in water hull cleaning is the impact it might have on the coating. If a technology provider claims that their system has no impact, or minimum impact on a particular type of coating that claim needs to be evaluated.

Anchor Chain Drag

During anchor deployment or retrieval, if the chain isn't properly guided, it can rub against the hull, especially in the forward section near the bow. This can cause significant hull paint damage. This friction causes wear and tear on the ship's hull paint, potentially leading to scratches. The chain's links can leave visible marks on the paint. In severe cases, the chain can actually strip away the paint completely, exposing the bare metal underneath. Once the paint is compromised, the underlying metal becomes vulnerable to rust and corrosion, leading to further damage, due to corrosion.

Some possible solutions could be chain length adjustment. Ensure the chain is long enough to prevent dragging. The length needed varies based on the ship's size, water depth, and local conditions. Inspection and maintenance of chain stopper regularly to ensure it's properly securing the chain. Also important is hull inspection and repair. Inspect the hull for any damage. If paint has been stripped, repair it promptly to prevent corrosion. This typically involves cleaning and sanding, removing rust and loose paint, application of primer and re application of antifouling paint.

Application procedure

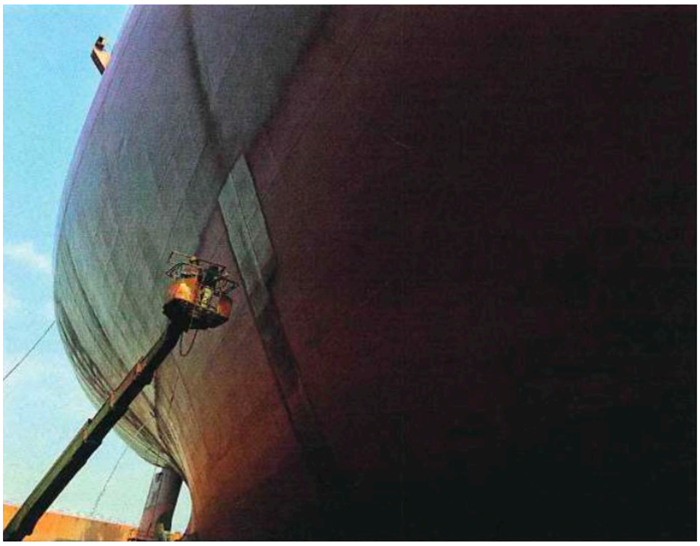
Surface preparation for coatings is specialized subject under corrosion protection and is subject to various standards available in the market, it is extremely important for any paint application be it for antifouling, primers, silicone coatings, topcoats, etc. There are standards from ISO and corrosion-focused organizations that would provide a deeper understanding into surface preparation. The guide here is to help readers grasp a basic understanding of surface preparation and what it entails.

Sand blasting is the most commonly used method of surface preparation whereby grit is fired at the surface to clean it and to provide a surface profile. This is a relatively fast method which is most effective on large areas. Although blasted steel is quite rough to the touch, the subsequent primer and antifouling coats are more than capable of providing a smooth finish. Sand blasting can be done with various types of grits available in the market with the most common being copper slag.

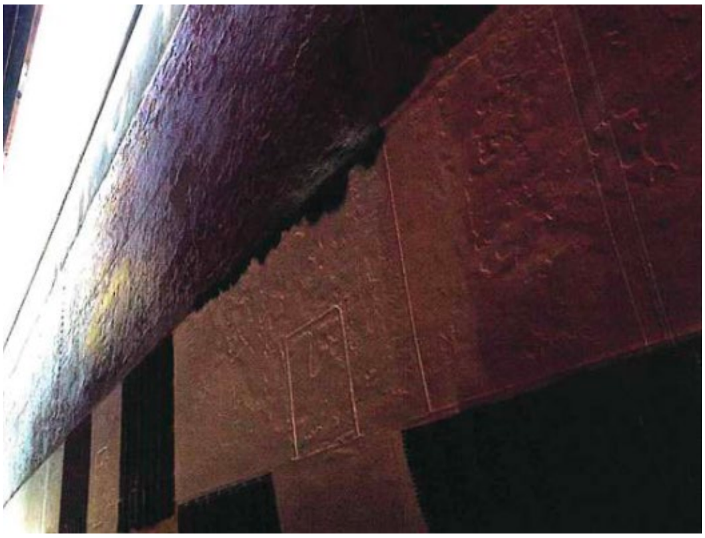
Spray painting equipment, includes spray pump , spray gun ,lance and nozzle. The majority of antifouling's are applied by airless spray as this is the most efficient method allowing coverage of large areas quickly, hence less time in dock or during block stage. The application conditions have a large impact on the final roughness of the surface. A rough hull can lead to increased fuel consumption and premature fouling. We should also take care to ensure the paint is distributed around the hull evenly to prevent early failure due to polishing.

As discussed in previous unit, surface roughness can contribute to reduced efficiency. It is important for ship owners and operators to understand this. It is recommended that a surface be fully blasted to ensure evenness and smoothness of the hull.

Below are examples of how a surface would look depending on choice of surface preparation.



Picture 9-An example of a fully blasted and even surface.



Picture 10-A rough surface like this would contribute to higher average hull roughness thereby reducing efficiency of the vessel.

Risk assessment of antifouling paints

The environmental hazards associated with the discharge of biocides from antifouling coatings are subject to stringent regulations aimed at safeguarding local ecosystems and harbors. In the risk assessment of antifouling coatings, it is essential to evaluate the release of biocides and other substances of concern, such as copper and zinc derived from copper oxide, copper pyrithione, and zinc oxide. According to the EU Biocidal Products Regulation, it is particularly critical to assess the release rates from vessels that are stationary in ports and harbors.

It is essential to assess the release of biocides and substances of concern, such as copper and zinc, from compounds like Cu_2O, CuSCN, and ZnO. According to the EU Biocidal Products Regulation (EU-BPR), measuring the release rate from recreational vessels while docked in enclosed marinas is particularly critical. In the future, it is anticipated that similar documentation will be mandated in ports and harbors..

The US Navy Dome method, developed by Seligman and Neumeister in 1983, represents the sole recognized technique for the direct in situ assessment of copper release from the hulls of moored vessels. This method is characterized by its high cost, impracticality for routine application, and challenges in standardization. While ISO standards exist based on laboratory experiments, two round-robin tests revealed significant inter-laboratory and intra-laboratory variations, leading to the conclusion that the results from these standards are not appropriate for direct application in risk assessments. The fundamental principle underlying this method is that a paint cannot release more biocide than what was originally present in the paint at the time of application.

When a vessel is secured at a mooring, the ISO 10890 method tends to significantly overestimate the rate of release, often by a factor of around three compared to the US Navy Dome. To enhance the accuracy of environmental copper release estimates in mooring scenarios, Finnie (2006) introduced correction factors.

Chapter 8: Hull cleaning during trading

The shipping industry is experiencing significant pressure to minimize its environmental impact and carbon emissions, while simultaneously confronting the risk posed by invasive aquatic species that threaten biodiversity and ecosystems. A viable approach to tackle these issues involves the implementation of a biofouling management strategy that integrates a specially formulated coating with an active in-water cleaning robot. This strategy is designed to maintain the cleanliness of ship hulls, which in turn reduces drag, lowers fuel consumption and emissions, and helps to prevent the proliferation of invasive species.

In-water cleaning (IWC) offers numerous benefits to researchers, coating manufacturers, and other professionals engaged in this field on a daily basis. However, these advantages are not effectively conveyed to stakeholders, including ship owners and regulatory bodies. Ship owners may undervalue the benefits of IWC while simultaneously overestimating the potential risks it poses to their coatings. Additionally, ports and relevant authorities often focus solely on the local risks associated with IWC, neglecting to recognize how it can enhance their sustainability initiatives. Consequently, their approach frequently becomes one of imposing restrictions on IWC rather than exploring its potential advantages.

In recent years, there has been a notable rise in the development and commercial application of Remotely Operated Vehicles (ROVs) for underwater ship maintenance tasks. These robotic systems are engineered to undertake a substantial portion of hull cleaning, thereby minimizing the necessity for diving operations. ROVs present numerous advantages over conventional diving methods, such as improved safety, consistent quality, and enhanced operational efficiency. Nevertheless, despite the increasing use of ROVs, diving operations continue to be crucial for executing repairs and cleaning in intricate or specialized areas, including propellers, sea chests, rudders, and bilge keels, where the effectiveness of robotic systems may be limited.

In a future where proactive management of biofouling has become the predominant and universally accepted method, integrated into the energy efficiency strategies of ship owners, a substantial market for IWC solutions will have developed. However, they are still many startups and projects even companies selling IWC products like ROVs (Remotely Operated Vehicles) and AUVs (Autonomous Underwater Vehicles).

High pressure underwater jetting

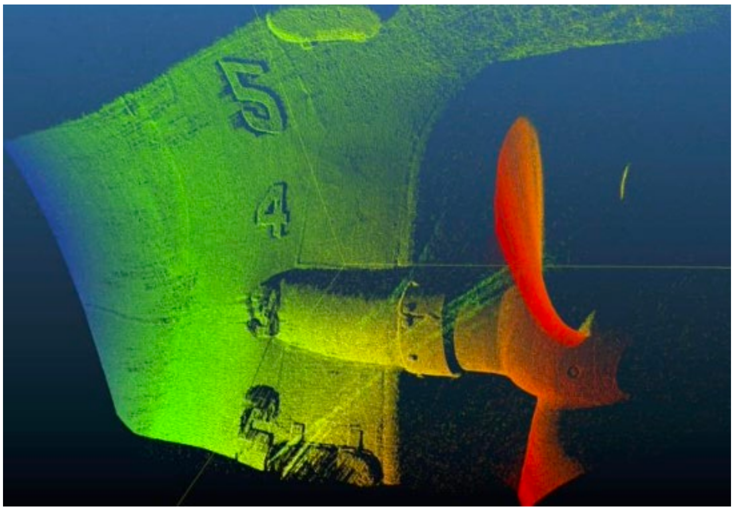
The new technology that is now more commonly used is high pressure underwater jetting, whereby a remote operated vehicle (ROV) attaches to the hull and uses high pressure water to remove fouling. This technology has been effective at removing slime and weed fouling. However, depending on the pressure applied, high pressure underwater jetting can be damaging to the coating.

They are powered by either electrical power only or a combination of electrical and hydraulic power, depending on the design. Controlled by a team of operators, utilizing video and other sensors for direct feedback to the operators during the hull cleaning process. Most ROVs rely on underwater thrusters for movement and positioning, however variations to this using magnetic pads as well as driven rubber coated wheels are also present in the market.

In water robotic cleaning and inspection continues to evolve in various aspects:

- Automatic identification and quantification of fouling using machine vision. Continuing development aims at aligning various machine vision system to use a common scale for rating of fouling on images.
- Laser scanning hull surfaces with resolution of 0.01 mm on crawling robots and 0.5 mm on free-floating robots. This resolution would allow quantification of macrofouling.
- Team-capable autonomous robots as the HSR robots of Armach Technology. Team capable robots can clean ship hulls in shorter time, parallelizing the work. A large cargo ship can then be cleaned during one regular port stay.

Picture 11-HSR robots (Armach Robotics)



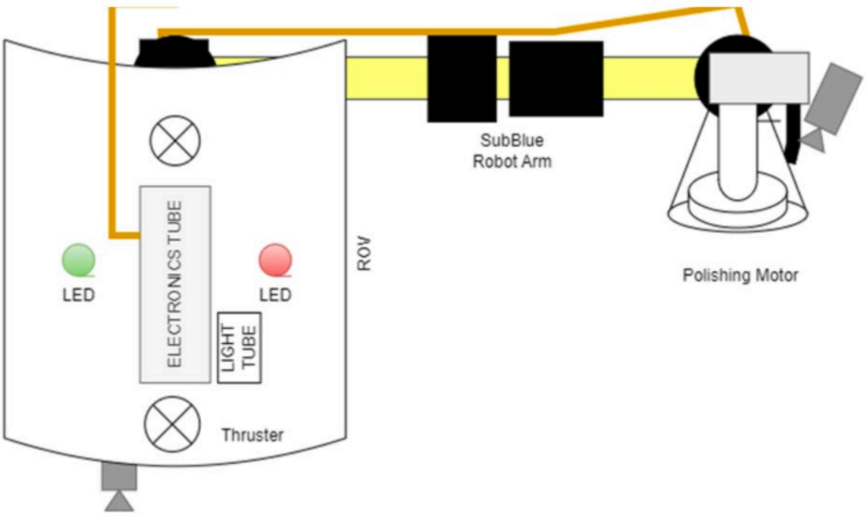
Picture 12-In-water scan from floating robot (Kraken Robotics)

<u>Propeller cleaning by robots</u>

Propeller polishing has conventionally been performed by divers or during the drydocking of vessels. Recently, hull cleaning robots have emerged in the hull cleaning sector, presenting competition to traditional diving methods. However, efforts to develop robotic systems for propeller polishing as a substitute for divers have not yet yielded success. These machines face several challenges, including the need to polish double-curved surfaces, manage polishing pressure while in a buoyant state, and address the limitations of depth perception when relying solely on a 2D camera.

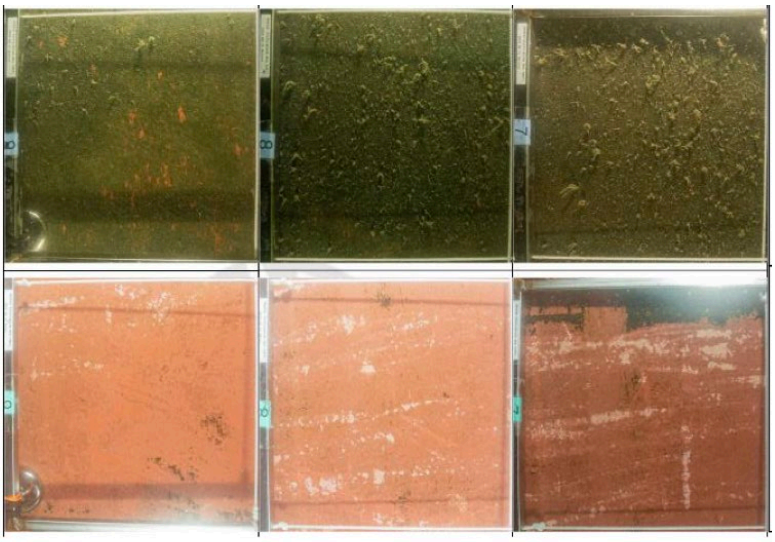
Additionally, they must navigate the complexities of a saline underwater environment, which poses various risks, such as the presence of rope cutters near the propeller.

Sub-Blue Robotics has introduced an innovative solution involving a remotely operated vehicle (ROV) equipped with a robotic arm featuring a five-degree-of-freedom manipulator and a polishing tool at its end. Once the ROV stabilizes itself in proximity to the propeller, the robotic arm can extend and maneuver across the propeller's surface, applying pressure while polishing. A diagram illustrating the robot's subcomponents is provided below. The fundamental technology consists of an ROV that utilizes thrusters to navigate from the berth to the propeller, along with a robotic arm fitted with a polishing tool.



Picture 13- Sub-blue presentation diagram

Upon securing its position adjacent to or on the propeller, the robot's arm can be extended, allowing the operator to manage it from the cockpit to polish the propeller blades. This robot is engineered to regulate the polishing pressure through traditional force control and orientation, enabling the operator to concentrate solely on steering movements. The existing force measurement is evaluated against the target polishing pressure, and the variance between these two values determines both the direction and magnitude of the motion increment in the pressing direction, thereby ensuring a relatively uniform polishing pressure is consistently upheld.



Picture 14- Before and after cleaning with ROV captured by certified divers.

TAS global has developed a reactive and proactive ROV cleaning robot. The fully automated unit is expected to be ready by mid to late 2025.

The maker claims the system is twice as fast as diver operations for cleaning.

The proactive cleaning system is said to be suitable for all types of AFS (soft or hard) because it does not use water jetting or rotating brushes, ensuring the removal of slime without damaging the paint.

Their views on the various type of the available ROV UWC:

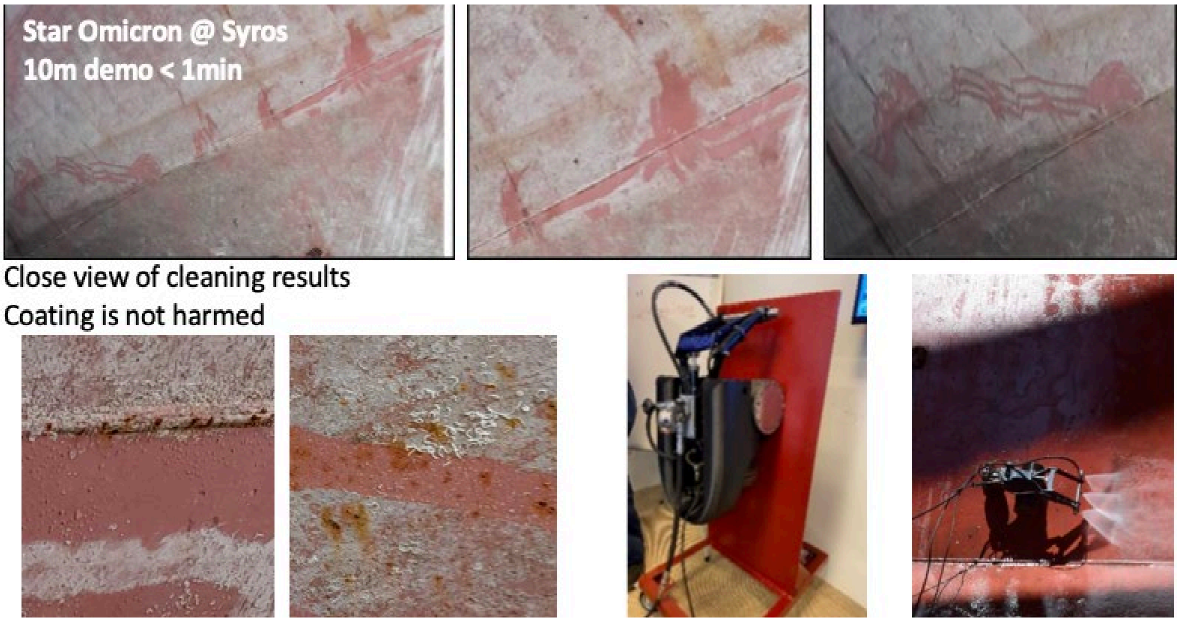
- Water jetting is not recommended as water can penetrate paint cracks and remove paint.
- Plastic brushes are suitable only for harder AFS and can damage softer AFS.
- Sponge/silicon brushes, which the company uses, are considered the ideal cleaning medium.

The company is developing a visual scanning system to create a shell expansion, draw hull lines, and produce a 3D model/scanning of the vessel. This 3D model can be used in the future to enhance robot cleaning accuracy.

The AI-powered camera can identify hull cleanliness with high accuracy and determine the type of biofouling present.

Glafcos ROV is an underwater cleaning and inspection robot for slime removal, suitable also for cargo hold cleaning, to be used by Crew Members.

It's a low cost system that launched in May 22' in Greece with no scheduling or complex logistics or high cost specialists. On the other hand, it is effective for slime only, not heavy fouling nor is it able to clean the propeller or treat 100% of the hull.



Picture 15- On site pictures from Star Omicron's inspection (Starbulk)

Conclusions

Hull fouling, a global challenge.

To conclude, the accumulation of micro- and macro- organisms on immersed surfaces of the hull, fouling, leads to environmental, economic and safety-related negative effects. Marine fouling generates surface roughness which increases the drag resistance of a ship moving through water and consequently increases fuel consumption and emissions.

The management of biofouling is an important vector that has potential to reduce ship's fuel consumption and thereby their CO_2 emissions. Currently, there is no doubt about the influence of GHGs on global warming and is negative impact on the environment and the world's sustainability.

Accumulation of fouling over time leads to significant drop in vessel's performance and increase in vessel fuel consumption and emissions

At the same time, global regulations regarding GHG and vessels' performance become stricter. Hull fouling is a huge problem and is estimated to account for 9% of the global fleets fuel consumption every year, this equates to roughly 80 million tons of excess CO_2 emissions and billions USD in extra fuel costs. A system that can reduce this problem is at the forefront of the shipping industry's thoughts.

This is a huge problem with industry giants spending millions looking for a suitable solution to meet the shipping industry's net zero 2050 goals.

Continual hull maintenance using best practice by antifouling coats, paints and proper cleaning is the best way for vessels owners to comply with IMO guidelines that are strict over environmental protection.

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