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The impact of biofouling on marine environment : a qualitative review of the current antifouling technologies

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THE IMPACT OF BIOFOULING ON MARINE ENVIRONMENT

A qualitative review of the current antifouling technologies

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Declaration

I certify that al the material in this dissertation that Is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect our own personal views, and are not necessarily endorsed by the University.

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Abstract

Title of Dissertation: The impact of biofouling on marine environment; A qualitative review of the current antifouling technologies.

Degree: Master of Science

This dissertation is a qualitative review of the harmful effects of biofouling on both the environment and the ship performance, and the technologies that have been used throughout history to prevent its adherence to the hulls of ships.

A brief review is carried out to present the historical approach to the evolution of antifouling systems and to identify the impacts of bio-fouling on the marine environment. A focused examination of the harmful effects of the transfer of invasive aquatic species (IAS) will be detailed. In addition, it will be explained how biofouling seriously affects the efficiency of the ship due to the increase in the roughness of the hull, among other factors. Problems related to the toxicity of the first antifouling paints that used compounds such as TBT will be explained.

As a response from the international community to this growing problem, legal instruments promoted by IMO and other specific regulations have been introduced in some of the most affected countries such as Australia, New Zealand and the United States, which will be mentioned in this work to clarify their capacity and limitations to address the problem from different aspects.

Moreover, a description will be given to the most used and available antifouling systems in the market, differentiating them according to their mechanisms of action, depending on whether biocides are used or not. This review will also include another significant point, such as in water hull cleaning, shore based antifouling paints removal. Finally, it will be, and according to the information as mentioned earlier through this dissertation to recommend which are the most appropriate antifouling systems, according to their efficiency and the environmental impacts, those might be produced to the aquatic system.

KEYWORDS : Biofouling, IAS, Antifouling, IMO, TBT, Ship Efficiency, Biocides, AFS Convention, Biofouling Guidelines, In-water Cleaning, Paints, GHG, Roughness, Australia, New Zealand.

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List of Abbreviations

AFRAMAX: Medium Size Oil Tanker 16
AFS: Antifouling System.......... 30
BDNs: Bunker Delivery Notes 40
BLG: Bulk Liquids and Gases 41
CDP: Controlled Depletion Polymer 54
CRMS: Craft Risk Management Standard.......... 48
DCS: Data Collection System.......... 41
DDT: Dichlorodiphenyltrichloroethane.......... 23
EE: Energy Efficiency 65
EEDI: Energy Efficiency Design Index.......... 20
EEOI: Energy Effciency Operational Indicator.......... 35
EPS: Extracellular Polymeric Substances.......... 26
FR: Foul Release.......... 61
GEF: Global Environment Facility.......... 45
GHG: Green House Gases 15
H.M.S.: Her Magisty´s Ship 51
HP: Horse Power 17
IAS: Invasive Aquatic Species 7
IEE: International Energy Efficiency 40
IMO: International Maritime Organization 40
MARPOL: International Convention For the Prevention Of Pollution From Ships . 20
MEPC: Marine Environment Protection Comitee 20
MGPS: Marine Growth Prevention Systems 43
ODS: Ozone Depleting Substances 20
PPR: Pollution Prevention and Response 64
SEEP: Ship Energy Efficiency Management Plan 20
SOx: Sulphur Oxides 11
SPC: Self Polishing Co-polymer 5

TBT: Trybutyl 5
TBTO: Tributyl Oxide 23
TEU: Twenty-Foot Equivalent Unit 16
TPhT: Tin Triphenyl 23
TPT: Triphenyltin 30
UNDP: United Nation Development Program 45
VLCC: Very Large Crude Carrier 16
VOC: Volatile Organic Compounds 20

1. Chapter I: Background

Biosecurity is a strategic approach that includes policies and regulatory frameworks with the purpose of analyzing and managing the associated risks for humans, animals, agricultural plants and threats relevant to the environment. Biosecurity has become a growing problem due to many factors, such as globalization, the increase of agricultural products and trade, the increasing movement of people between different countries, the lack of communications and access to information on biosafety, and the shortage of operational and technical resources. An important factor related to the maritime industry is the high dependence on goods and products imported by sea. In fact, 90% of world trade is transported by sea, making ships potential sources of biological risk for the transport of invasive species (FAO, 2007).

As mentioned above, ships can carry different elements of risk for biosecurity: from the food used for the crew or passengers to the cargo transported in containers. The threats can be divided into different areas such as health care, waste treatment, invasive species, and ship stores. Each one of these possible threats represents a high risk for people´s health as well as for the economy and the environment. In the case of health care, particular caution should be taken in respect to the risk of disease transmission by crews and passengers of vessels, establishing quarantines if necessary to prevent massive contagion and the spread of deadly diseases such as Ebola. Another crucial aspect to consider is the adequate treatment of garbage and ship waste to avoid the proliferation of pests, rats, and insects and to preserve the quality of the environment, avoiding discharges in protected areas. However, according to FAO, the problem with the ship stores is mainly related to the storage and use of food products destined for the crew or passengers. Customs or other sanitary authorities do not control these products such as uncooked meat, vegetables or fruits representing potential entry routes for pests or diseases.

The last factor to consider regarding threats to biosecurity is invasive species. Non-native marine organisms (plants, animals, pathogens, and diseases) are one of the greatest threats to biodiversity and the health of the world's ocean ecosystems. This phenomenon is continuously growing and, unlike oil spills, instead of decreasing over the years, it has been increasing (Raaymakers, 2002). Ships play an essential role in the transport and translocation of non-native marine organisms through two means of transportation of exotic species. The first and best-known way of transport of invasive species is through the ballast water of ships. Aquatic organisms have had the possibility to travel by boats since the first ancient civilizations began to venture out to navigate the oceans. Today these organisms are traveling in the ponds of ships in ballast water, which is composed of water, sediment, and millions of small living species. Every day around 4000 aquatic species travel around the world, from bacteria to fish. All of these species are exotic, foreign or invasive in the new destination they are moving to, which means they could cause a possible biological invasion with a significant ecological impact.

The second way of transport of non-indigenous organisms is by biofouling, whether attached to the external surface of the vessel or within its local seawater system. Over the years, this vector has been given less importance than the introduction by ballast water, although recent studies have discovered that biofouling could be the highest translocational method of non-indigenous species. According to a study conducted by Molnar in 2008, out of a total of 329 IAS considered for the study, 39% of these species were introduced by Biofouling, and 30% by ballast water. This high percentage of transported species highlights the importance of anti-fouling systems as a solution (Department of Fisheries, 2009).

The marine biological fouling is a term describing the phenomenon of accumulation of undesirable marine organisms or animals and plants on an immersed surface in seawater (Yebra, Kiil, & Dam-Johansen, 2004). One of the effects of marine fouling on ships and the environment: is an increase of frictional resistance, which leads to the reduction of ship speed. This is due to the increase in weight of the ship, which then requires more fuel consumption to compensate the speed loss. Increased fuel consumption, in turn generates more harmful emissions and that is another environmental issue (Rascio, 2000). A further impact is an increase in dry-docking operations. Besides loss of time and waste of resources, the methods used to solve this issue generate contaminating substances (Abbott, Abel, Arnold, & Milne, 2000). Furthermore, non-native species are translocated to a new marine ecosystem where they were not initially present (Brancato, 1999). However, anti-fouling systems have been introduced to overcome the issue of the accumulation of biofouling on ship's hulls. Among all types of solutions, tributyltin self-polishing copolymer paints (TBT-SPC paints) Have been the most successful solution to prevent biofouling. The use of TBT-SPC paints has spread widely, now covering 70% of the world fleet (Gerigk, Schneider, & Stewen, 1998). Unfortunately, the TBT-SPC systems have a severe effects on the environment, for instance, causing defective shell growth in mollusks and also it caused the development of male characteristic in female genitalia (Evans, Leksono, & McKinnell, 1995). After the AFS convention held in 2001, the state parties banned the application of TBT based anti-fouling paints from January 2003. It was further required to remove its presence from ships' surfaces in 2008. Subsequently, the paint industry has been urged to produce TBT- free based antifouling - paints instead of TBT-based which have the same economic benefits and are less harmful to the environment. Thus, companies responded positively by starting to produce TBT-free paints from 2003. Moreover, the other interested parties including shipping companies began to undertake an extensive fleet conversion to comply with the AFS Convention (Champ, 2001).

1.2 Aims and objectives

The main objectives of this dissertation are :

- To clarify the implications related to anti-fouling and marine ecosystem
- To introduce a comparative analysis of the most used anti-fouling systems
- To recommend the most appropriate anti-fouling systems

1.3 Research question

What are the impacts of anti-fouling systems on the marine environment and how can they be minimized by choosing the best technologies available in the market.

1.4 Methodology

The methodology of this dissertation has a qualitative character, analyzing the problem of marine pollution produced by the anti-fouling systems used to mitigate the issue of non-indigenous species that transported by ships' hulls. Scientific literature and online sources are reviewed and analyzed in order to provide hard data for this research, together with information provided by experts in paint and antifouling technologies.

This research begins with a brief historical description of the antifouling technologies used over the years. Secondly, the harmful effects of biofouling and its economic and environmental impacts are described. For this purpose, scientific papers and online sources are used.

Through analysis of the sources of information, the research describes how invasive species are attached to ships' hulls and how they are transported. The research describes and analyzes the measures adopted by IMO and the international community to combat invasive species and how one of the most effective methods, anti-fouling ,has become a contaminating source for marine species due to its toxicity. Finally and after collecting all the necessary legal and technical information, new technologies in biofouling control are analyzed.

1.5 Expected results

- To determine the relationship between Invasive Aquatic Species (IAS) and the Biofouling transported by ships.
- To demonstrate the importance of biofouling on board vessels and how it affects the ships' efficiency and operational costs.
- To clarify the impacts of the anti-fouling systems on the marine environment
- To evaluate current anti-fouling systems and show their impact to the environment.
- To analyze the technical information obtained and compare the available technologies related to antifouling systems, in order to determine which, one has the least impact on the aquatic environment.

1.6 Limitations

The availability of resources to identify the currently used anti-fouling technologies is limited for two main reasons, which are market competition and the overlap of technical information. However, expert publications and interested international environmental organizations are valuable sources of verified and confirmed data to be analyzed as mentioned earlier in the methodology. Another limitation is related to the technical aspect of the investigation, when evaluating the characteristics of an anti-fouling system versus another type of method. Another barrier to the normal development of this investigation could be the time used in obtaining the data. This, added to the regular academic activities and field trips, could affect the real-time used in the research.

1.7 Scope of the work

- The primary focus of this research is on the impacts of anti-fouling systems, but it will not be limited to that subject alone. Topics such as invasive species and ballast water will be discussed.
- With regard to biosecurity, issues such as ballast water and bio fouling will be analyzed; however, other issues related to biosecurity risks such as garbage management, health, and quarantine of crews and the care of transported loads will not be reviewed due to the fact that they are not directly related to bio fouling and antifouling pollution.

2. Chapter II - Biofouling and Anti fouling impacts on marine environment

In this chapter, a definition of biofouling will first be given, and then briefly describe the evolution of antifouling systems over time and how the first navigators solved the problem of the adhesion of organisms to the hull of their ships. As it can see throughout this chapter, the issue of biofouling remains until modern times, causing various serious problems such as the transfer of IAS; Problems related to ship efficiency and the operational costs of the ships, while increasing the emissions of GHG and finally the problem caused by solutions developed with toxic compounds such as antifouling paints containing TBT. By the end of this chapter, the process of biofouling formation with its respective stages will be described, and the factors that affect the creation of these organisms will be mentioned.

Biofouling is the process whereby microorganisms, plants, algae or animals adhere to and accumulate on wet surfaces (Strietman & Leemans, 2019), or as defined by IMO, "*biofouling is the accumulation of aquatic organisms such as micro-organisms, plants, and animals on surfaces and structures immersed in or exposed to the aquatic environment. Biofouling includes microfouling and macrofouling" (IMO, 2011)* The process of fouling is detailed in the chapter 2.3

2.1 Historical approach to Biofouling

The problem of biofouling could be said to be as old as navigation itself. From the moment vessels were placed in the water in ancient times, thousands of aquatic organisms found new surfaces to grow on and develop, as well as to feed themselves. The adherence of these organisms to ships had several consequences, such as the corrosion ship structures, impacts on ease of maneuverability, and reduction of the useful life of ships. Essentially, these impacts put the integrity of the vessel and its cargo at risk (Alonso, 2011).

This unwanted phenomenon of biofouling has affected ships for hundreds of years, since humanity has been sailing the seas. One of the first references about fouling on ships that can be found in history is related to a small fish called Echeneis or Remora. As described by Aristotle in the 4th century BC, there was a belief that the Echeneis or Remora could decrease the speed of a ship and even stop it (Stephens, 1952). However, Plutarch, around 100 AD, pointed out that fouling was responsible for the problems of delay and low speed of ships, indicating that "*when weeds, ooze, and filth stick upon its sides, the stroke of the ship is more obtuse and weak; and the water, coming upon this clammy matter, doth not so easily part from it; and this is the reason why they usually calk their ships*" (Plutarch, 2013). These statements made by Plutarch are one of the first mentions in history of biofouling on ships.

2.2 Identified impacts of Biofouling and Anti-Fouling systems

The set of bio-organisms that grows on submerged structures is composed of hundreds of species such as bacteria, protozoa, algae, mollusks, and hydrozoans, among others. These organisms, which often add up to more than 150 kilograms per square meter (Alonso, 2011), adhere firmly to the surface of the hull, growing rapidly and with great potential for reproduction.

As a consequence of this adhesion process, fouling accelerates the corrosion of materials and causes losses in the operative efficiency of ships. These damages affect the vessels, oil or gas platforms, research instruments, aquaculture facilities (aquariums, cages, conduits, pumps) and the cultivated organisms themselves.

The effects produced by biofouling can be approached from three points of view or aspects:

- The toxicity of antifouling paints: The risk for marine ecosystems when using chemical products such as paints with biocides to eliminate biofouling. By using this type of paint, containing highly polluting biocides such as TBT, estuaries, bays, open

sea, commercial ports, marinas, seafood extraction areas, and fishing areas are at risk (Almeida, Diamantino, & De Sousa, 2007).
- Ship efficiency and operational and economic problems for the navigation of the ships: When the ships have a layer of biofouling on the hull, this produces higher resistance to water, as a result of the friction existing between the dirty hull and the sea or better-called hull-water hull interface. This resistance reduces the speed of the ship and increases fuel consumption while reducing the maneuverability of the vessel, and necessitating more stops for maintenance and cleaning of the hull as well as dry dock work and all its associated expenses (Kemal, Turan, & Incecik, 2017).

- Environmental risks and the introduction of invasive species: Biofouling along with ballast water is one of the main contributors to the introduction of invasive species into sensitive ecosystems. This has been recognized even by the International Maritime Organization (IMO). Considering the current dimensions of modern ships and their hulls, and the large number of vessels sailing in the oceans, estimated to be more than 50 thousand merchant ships (Marine Flottenkommando, 2018) there is reason for concern about biofouling and its effects on the world. The increase in fuel consumption as a result of the incrustation of the hull of the ship leads to serious environmental problems, such as the increase of emissions of greenhouse gases (CO2, Sox and NOx) to the atmosphere, and resultant the increase in precipitation of acid rain that, which, in turn, lowers the pH of the oceans affecting marine life.

Another point to consider in the problem of invasive species is the growth of recreational navigation and marinas, which are not always subject to the same maintenance as a larger vessel and can transport biofouling between marinas of different countries. Finally, the aquaculture industry is also affected by biofouling, by adhering to the cages of the marine centers.

If we analyze the previous points of view, it is possible to determine that the most notorious and harmful effect on marine ecosystems has been the unwanted transport of species attached to the hulls of ships. This problem is even more severe in transoceanic vessels, which sail long distances, from and to very different ecosystems. Due to this transport of unwanted organisms in the hulls of ships, native species of certain seas can become a plague thousands of kilometers from their habitat of origin when they are detached either for natural reasons or for cleanliness. An example of the gravity of invasive species is the case of zebra mussels (Dreissena polymorpha) in the Great Lakes of North America. The zebra mussel is native to the seas of northern Europe; however, and as a result of its transport on merchant ships to America, it became a serious plague that is destroying much of the biodiversity in lakes and rivers (McAvoy, 2013).

2.2.1 Introduction of alien species through biofouling

Throughout the past millennium, aquatic species have moved freely across the world's oceans only by natural means, such as ocean currents, climatic conditions, surface ocean winds, or adhered to floating logs. The existing barriers to their propagation have been natural biological and environmental factors, such as temperature, salinity, landmasses, and natural predators. However, this has changed over time, which has caused an increase in the number of invasive species that are transported to various regions of the world. The increase is due to several factors such as human activities that make it possible for species to cross natural barriers.

Therefore, many marine and coastal species have been able to establish new populations outside their native limits and potentially threaten native species or cause significant ecological and environmental damage, becoming a threat to humans and in many cases having a severe effect on the economy. Other factors that influence this increase in the transfer of species are global warming, the higher number of ships that currently exist and the greater number of commercial sea routes as can be seen in Figure 1. Global Warming weakens specific natural barriers such as the melting of ice in polar areas while opening new trade routes where ships can travel.

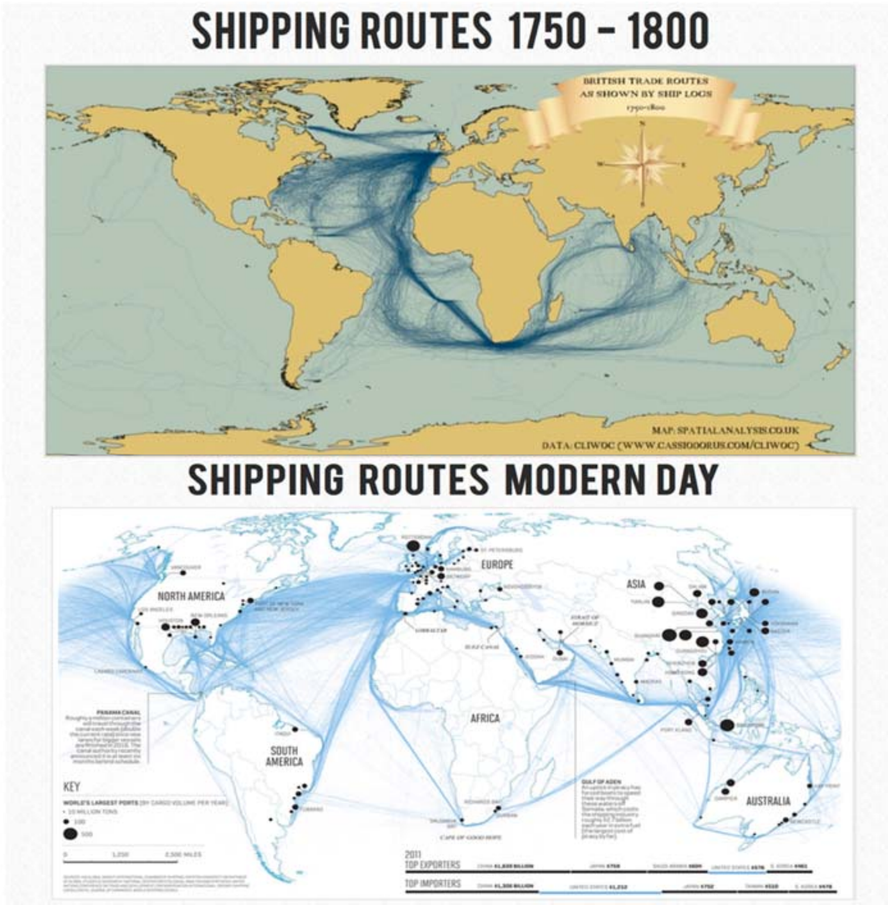

Figure 1 Differences between shipping routes in old times and modern times.

Retrieved from http://www.geographypods.com/2-changing-space---the-shrinking-world.html#

The movement of invasive aquatic species has shown a dramatic increase in frequency, extent, and damage over the last 50 years, and this is mainly due to their transfer via the shipping industry. According to a study in which information was collected from more than 350 databases, samples and other sources, the results showed that of the 329 marine invasive species considered in the study, shipping was the most common introduction route with 69% of the total, while aquaculture represents 41%, channels 17%, aquarium trade 6%, and finally live seafood trade (2%) (Molnar, Gamboa, Revenga, & Spalding, 2008). In the same study, of the 205 species introduced via shipping, 39% were introduced by hull-fouling, 31% via ballast water, and the remainder by both (Jackson, 2008).

According to a study by Hewitt and Campbell (2008), it has been estimated that of a total 1,781 invasive aquatic species registered in harbours and ports around the world, 55-69% of these species were introduced through biofouling on ships. These studies serve as an example to demonstrate the importance of maritime transport in the introduction of invasive aquatic species compared to other routes of entry, and especially the role that biofouling plays as a vector and why it is considered even more important than the introduction of species through ballast water.

The importance of biofouling in the introduction of invasive aquatic species was highlighted in 2007 IMO document BLG 12/11, development of international measures for minimizing the translocation of invasive aquatic species through biofouling of ships , presented by Australia and New Zealand. The aforementioned document states that biofouling is accountable for:

- *74% of non-indigenous marine invertebrates transported to the Hawaiian Islands.*
- *42% of marine species unintentionally introduced into Japan.*
- *69% of adventive marine species arrivals in New Zealand, with a further 21% possibly as biofouling or in ballast water.*
- *78% of introduced marine species in Port Philip Bay, Australia.*
- *More than half of the ship-mediated species introductions into the North Sea, and*
- *70% of the species that have invaded coastal North America via ships have either been moved by biofouling alone, or could have been moved by biofouling and ballast water (Jackson, 2008).*

Effect of the Invasive Aquatic Species

The introduction of invasive species into a new environment can have serious consequences for the environment and local biodiversity, economic consequences for industries and users of natural resources, and negative consequences for the health and well-being of those who live near affected marine environments.

In general, the effects of invasive species can be divided into three categories: Ecological, Economic and Health-related; however, this last category is more related to the transfer of diseases such as Cholera through ballast water and not biofouling.

Ecological impact

Invasive organisms can modify ecosystems and trophic chains by displacing endemic organisms or becoming pest organisms in the region. Another effect of IAS is the pathogenic microorganisms that could cause diseases to the macro-organisms of other areas by decreasing their population and modifying the surrounding architecture. Although it is true that the initial impacts may be minor and almost invisible, as the invasive population increases over time, the impacts will increase in severity. In addition, once a species has been introduced, it is very difficult if not impossible to remove it (Tun-Che, 2018).

Among the most common environmental impacts produced by IAS, it is possible to mention the competition with native species for space and food and the potential extermination of the latter. The impacts of the alteration of the habitat, the natural environmental conditions and the food web of the local species cause the displacement of the native species, which reduces biodiversity and in some cases causes the extinction of local species.

Economic Impacts

The introduction of IAS in new ecosystems produces a strong economic impact on the society because it is necessary to consider both economic losses due to reduced productivity, as well as the costs incurred for the prevention and management of invasive species. Specific examples of the economic impacts of IAS are:

- Reductions in fishing production due to competition, predation or displacement of fishing species by invasive species, and/or by environmental / habitat changes caused by invading species.
- Impacts on the aquaculture industry, which include the closure of many local facilities, especially when affected by dangerous algal blooms.

- Physical impacts on infrastructure, facilities, and coastal industries, which are affected by corrosion and by species like the zebra mussel.
- Reduction in the economy and efficiency of navigation, due to the encrustation of species.
- Closure of recreational and tourist beaches and other coastal tourist sites due to invasive species
- Secondary economic impacts from ecological impacts and loss of biodiversity
- Costs associated with public health to treat introduced pathogens and toxic species

2.2.2 Biofouling effects on Ships Efficiency

The maritime industry has been and is still making efforts in order to decrease GHG emissions and its impact to the environment. For that reason, stakeholders are undertaking measures that improve the ships' efficiency to reduce fuel consumption to achieve the target of less emissions. Further, different factors are involved in the process of improving ship efficiency with respect to reducing fuel consumption, for instance, operation condition (ship draft , trim , speed); weather condition; engine performance; ship profile (ship type, size , location, etc.); and hull smoothness (the percentage of fouling accumulation on the vessel's hull and propeller) (Giorgiutti, Rezende, Van, Monteiro, & Preterote, 2014). Furthermore, In order to address this issue, it is important to mention the overall equation that represents the major factors that contribute to ship efficiency. This equation is the Biofouling accumulation, the ship hull roughness which is related to the drag force, the ratio of fuel consumption, and the amount of produced emissions.

Biofouling Accumulation Impact to Ship Resistance

Ships are normally exposed to different types of resistance affecting their efficiency; however, the main three factors increasing ship resistance are the form or shape of the vessel, wave making resistance, and frictional resistance (Anderson, 2016). The frictional resistance is caused by the accumulation of fouling on ships' hulls. The attachment of marine species has a significant impact on ship performance and efficiency because it increases the ship's hydrodynamic volume, which could increase the drag force by up to 60%. This equates to more than 10% reduction of the ship speed and approximately 40% growth of fuel consumption in order to maintain the required speed (McElvany, 2009). Moreover, experimental studies had been carried out providing valuable information on the impact of roughness on frictional resistance.

The first experimental study on hull roughness and its impact on frictional resistance is attributed to Froud (1874) and was carried out in the late 18th century. Another experiment was conducted but with more focus on "barnacles" on the hull. The outcomes showed a rise in frictional resistance up to four times after exposure to sea water for 12 months, compared with the resistance of otherwise identical samples with clean hulls (McEntee, 1916). Kempf carried out tests on pontoons covered with shell fouling and predicted the resistance according to the rate of coverage. He recorded the maximum resistance elevation when the coverage by barnacles is 75%. In contrast, drag force was increased by 66% when the barnacle coverage was only 5% (Kempf, 1937).

Lastly in 2016, an experiment found an increase of drag coefficient up to 34% in the total resistance of a very large crude oil carrier due to light calcareous tubeworm fouling (Monty et al., 2016). In any case, frictional resistance is mainly controlled by the roughness on the ship's hull.

According to the previous mentioned experiments the importance of the issue of fouling on ships' operational efficiency is clearly indicated. Thus, there is a significant need for anti-fouling systems to minimize this phenomena. To illustrate, Figure 2 shows the different types of resistance that affect ship efficiency with regard to the ship profile (Tanker ships , Container ships). The four types of resistance are Air, Wave-making, Appendages, and Viscous "Frictional".

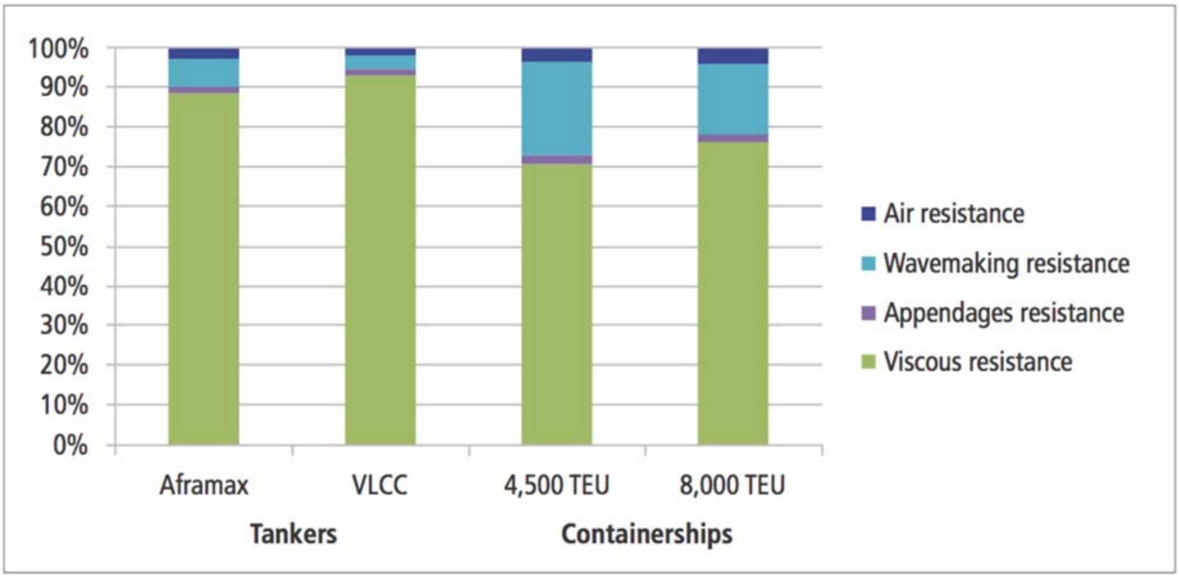

Figure 2 Hull Resistance In Calm Water at Design Speed

Source: ABS Ship Energy Efficiency Measures Advisory

As shown in Figure 2, the frictional resistance is the greatest among all other types for all ship profiles. However, it is higher for tanker ships compared to containers, which reflects two main reasons. First, the size of the submerged portion is higher in tankers. Second, relative speed is slower in tankers compared with containers. The frictional resistance has a significant effect on all type of ships. According to Figure 2, it starts with approximately 70% for the least affected type of ship up to 95% for the highest. In addition, there is a substantial relationship between the ship velocity and power with correspondence to the frictional resistance on the hull. Figures 3 and 4 indicate that as resistance increases, ship power increases or speed declines; either way ship operational costs rise. Figure 3 shows the impact on ship speed due to fouling on its hull and propeller.

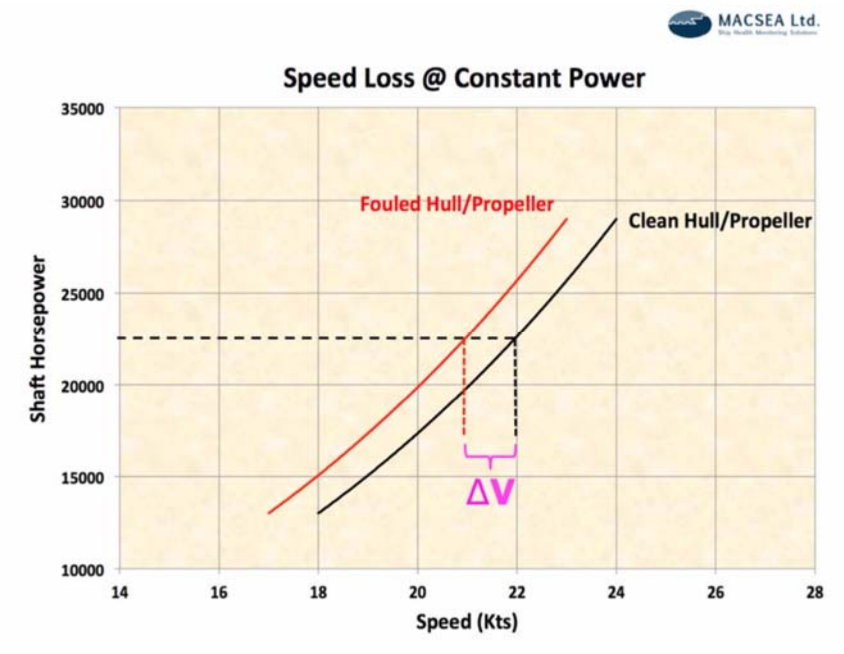

Figure 3 The effect of frictional resistance

Source: Ship Health Monitoring Solutions "MACEA Ltd."

As shown in Figure 3, at constant power with around 22500 HP, the ship with fouled hull and propeller tended to have less speed, around 21 knots. On the other hand, the ship with a clean hull and propeller achieved a higher speed of 22 knots at the same power.

Moreover, Figure 4 shows how power increases with the fouled ship hull/propeller to maintain the same speed as a clean ship.

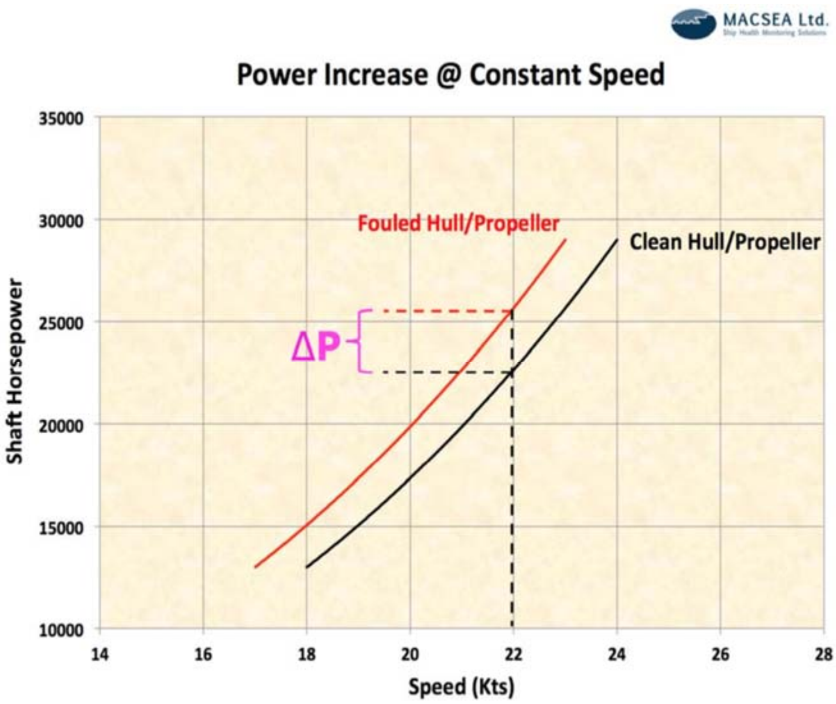

Figure 4 The effect of frictional resistance,

Source: Ship Health Monitoring Solutions "MACEA Ltd"

In this figure it is undeniable that the ship with fouled hull/propeller has to consume more power to achieve the same speed with the cleaned ship, where the power needed to achieve 22 knots is approximately 22500 HP for the clean hull/ propeller ship, while an elevation of 3500HP is required to maintain the same speed on the fouled hull/propeller ship.

Biofouling is mainly composed of two categories, biological and physical fouling. Physical fouling creates a biofilm on the ship's hull by Micro-organisms and Macro-scaling, or "Macrofouling" (Hellio & Yebra, 2009). In addition, the inorganic fouling is composed of corrosion, crystallization, suspended particles, oil, and ice. In other words, the term of Biofouling combines all the earlier categories (Micro organisms, Macro organisms, and inorganic attachments (Bixler & Bharat, 2012).

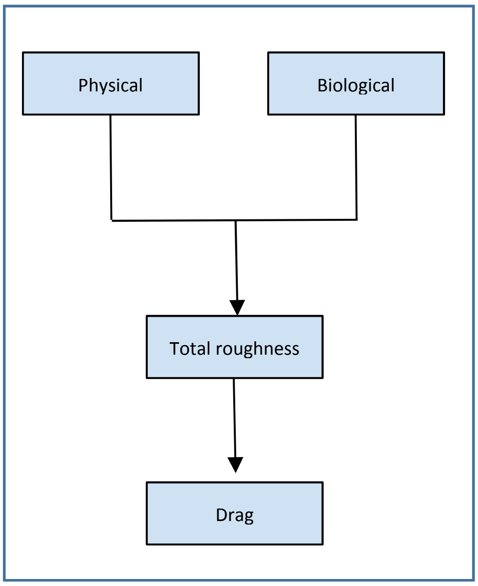

Figure 5 General Components causing roughness Source: Colin Anderson Presentation

The general components causing roughness on the vessel hull are as mentioned in Figure 5, which include the physical elements in addition to the biological parts. Moreover, the physical elements include Macro and Micro roughness. For example, Macro roughness can be corrosion, tug marks, or cavitation. Such kinds of roughness cannot be controlled by antifouling applications but require structural design and operational mitigations (Anderson, 2016). On the other hand, the biological roughness contains two categories as follows:

- Animal: Which includes soft bodied and hard shelled (Barnacles, Tube Worms and Mussels)
- Plants: Microalgae (Slim) and Macroalgae (red, green and brown weeds)

The impact of Macro or Micro plant fouling besides the animal fouling in the ship efficiency by increasing the drag could be vary from type to another. For instance, the slime (Micro) fouling could increase the drag force of a ship to 10% while weed (Macro) fouling responsible to increase the drag force more than 10% (Anderson, 2016).

Moreover, animal fouling is considered the greatest influencers on a ship hull roughness where the shell fouling could elevate the drag force up to 40%, which is a great challenge to the ship efficiency (Anderson, 2016).

Figure 6 Shell fouling accumulation

Source: www.TimesofOman.com

IMO Approach to address ship efficiency

IMO has played an important role in order to reduce the impact of biofouling to the environment by introducing the Biofouling Guidelines which stress the mitigation measures to be carried out by all stakeholders in the maritime industry (IMO, 2011). In addition to the biological threats, IMO has noticed the importance of the economic issues caused by the accumulation of biofouling on ships hulls in terms of fuel consumption and ship efficiency, which could increase harmful fuel emissions. Moreover, MARPOL Annex VI Prevention Of Air Pollution From Ships (MARPOL Annex VI), first adopted in 1997, limits the main air pollutants contained in ships' exhaust gas, including sulphur oxides (SO_x) and nitrous oxides (NO_x), and prohibits deliberate emissions of ozone depleting substances (ODS). MARPOL Annex VI also regulates shipboard incineration, and the emissions of volatile organic compounds (VOC) from tankers (MARPOL, 1973). Further, at MEPC 62 (July 2011) an adoption of amendments to MARPOL Annex VI introduced a new chapter 4, as a result of IMO debate on ship efficiency, and subsequent agreement on new regulations were introduced as follows: Reg.19 Application, Reg.20 Attained EEDI (The Energy Efficiency Design Index), Reg.21 Required EEDI, Reg.22 SEEMP (Ship Energy Efficiency Management Plan), Reg.23 Promotion of technical co -operation and transfer technology relating to the improvement of energy efficiency of ships (MEPC, 2006). Furthermore, SEEMP established a mechanism that helps operators to improve their ships' energy efficiency, namely Regulation 22 of Chapter 4 specifically requiring to keep onboard a ship energy efficiency management plan. The shipping industry is concerned about the pollution that is caused by ships emissions, thus, tools have been established to ensure the reduction of the CO_2 emissions are carried out with the most effective solutions e.g. structural and design and operational (Hughes, 2013). However, EEDI has been developed for the largest and the most energy intensive merchant fleet, for instance, tankers, gas carriers, bulk carriers and general cargo ships, but it is not applicable for all type of vessels e.g. ships with diesel-electric engines, turbine and hybrid systems which need more corrected factors. Indeed, all vessels of 400 gross tonnage and above engaged in international trade have to comply and implement the SEEMP, which establishes a mechanism to improve the ship energy efficiency in addition to helping the operators to monitor their ship engines performance at regular intervals considering new technologies to improve the efficiency (Edmund Hughes, Technical Officer, Marine Environment Division, IMO, 2013). Moreover, SEEMP will give the operator the incentive to reduce the fuel cost for their benefits by implementing SEEMP as the regulation does not set any requirements on how to reduce the fuel; therefore, it will be completely up to the industry to utilize it for their interest. In addition, a set of guidelines were adopted by IMO MEPC 63 (MARCH) (MEPC.219(63), 2012) in the same context to assist in the implementation of the mandatory regulations of energy efficiency of ships by MARPOL Annex VI as follows:

- Resolution MEPC.212(93) – 2012 Guidelines on the method of calculation of the attained Energy Efficiency Design Index (EEDI) for new ships;
- Resolution MEPC.213(93) – 2012 Guidelines for the development of a Ship Energy Efficiency Management Plan (SEEMP);
- Resolution MEPC.214(93) – 2012 Guidelines on survey and certification of the Energy Efficiency Design Index (EEDI);
- Resolution MEPC.215(93) – Guidelines for calculation of reference lines for use with the Energy Efficiency Design Index (EEDI).

SEEMP should be designed as a specific plan by the shipowner, charterer or any party concerned. The SEEMP plan seeks to improve the ship energy efficiency through the following steps:

- Planning
- Implementing
- Monitoring
- Self-evaluation and improvement

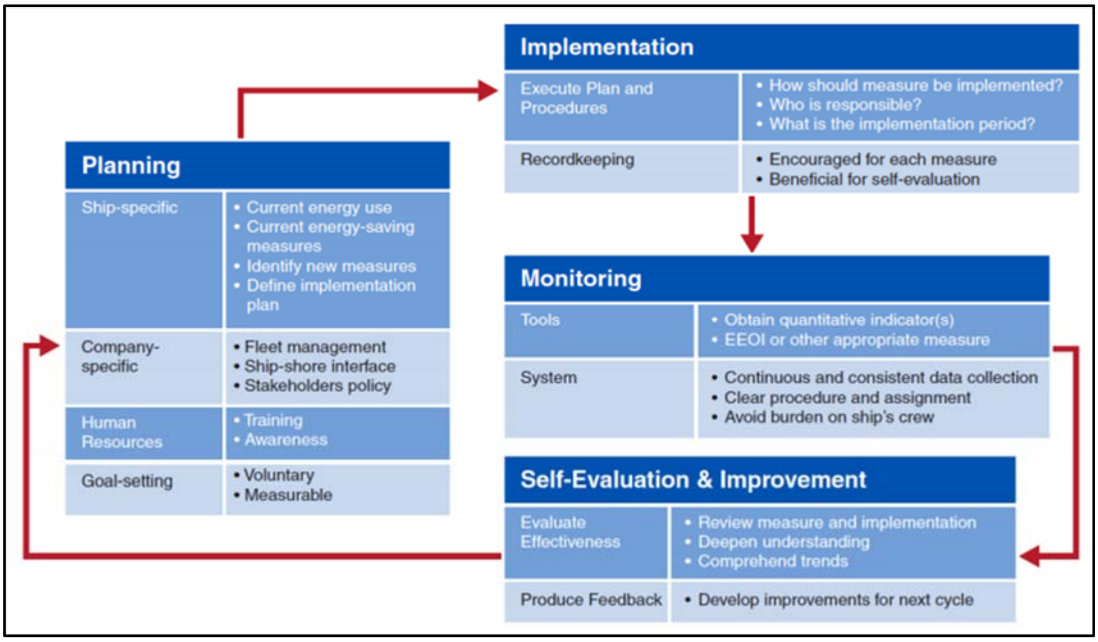

Figure 7 The four steps of SEEMP

Source: ABS

The four step procedures start with planning where the ship and the company specifics can be set. The implementation step follows where the execution procedures are determined, and later, the monitoring step, which contains the indicators and parameters. Finally, the self-evaluation and improvement step follows, where the measures, implementation and feedback are revised to develop the improvement for the next cycle. On other hand, the fuel consumption is assumed to be significant to the maritime industry, in terms of cost and the environmental. However, SEEMP, which is a tool introduced by IMO, is a mechanism that could improve the ship energy efficiency which could reduce the operational cost by reducing the fuel consumption besides minimizing the environmental impact of the CO2 emissions.

2.2.3 Toxicity in Antifouling Paintings

As a way to deal with the problem of invasive species and the problems caused by biofouling in ships, over the years, different chemical products have been used to inhibit the development of bio-fouling. Chemicals affect organisms that colonize natural surfaces such as coral reefs and epilithic biofilms. Most developed antifouling products use metals such as copper as biocidal agents. However, copper is suspended in the water column and reaches other macroorganisms such as algae and bivalves, which can also affect the biofilm structures (McKensie, Brooks, & Jhonston, 2012).

Numerous organometallic compounds have been studied as biocides, including those of the RMeX type, where R is an organic radical, Me is the metal and X is a halide or an acidic moiety. Among these last, reference should be made to organomercury, organoarsenic, organoplome and more recently RsnX organotin compounds (Gabaldón, n.d). Among the latter, the best known and used during the 60s - 70s and until its ban not many years ago was Tributyltin (TBT) and its derivatives. The main biocidal active compound of ship paints during these years was tin tributyl (TBT) usually provided as tributyl oxide (TBTO) and also tin triphenyl (TPhT). The TBT was highly effective against the adhesion of a wide range of organisms. However, scientific studies have shown that this compound is very persistent in the marine environment and significantly alters the biology of a large number of organisms in very low concentrations, of the order of nanograms per liter, to the point of producing among other alterations in various marine organisms, sexual mutations in mollusks and snails (Barreiro, Quintela, & Ruiz, 2004; Laughlin, 1996).

TBT and its impacts

TBT causes alterations in the endocrine system of marine mollusks and also causes the development of male characters in female snail. This biocide also damages the immune system, and very low exposures in mollusks are responsible for malformations in the shell. TBT is widely dispersed throughout the marine environment and has been found in the tissues of cetaceans, seals, sea otters, and seabirds throughout the world. Tissue and sediment samples from areas with intense navigation activity show the highest concentrations of contamination.

As for the toxicity in the marine environment of TBT, it can cause both fatal and sub-lethal damage in different taxonomic groups and at different levels of organization, from biochemical alterations to local extinctions. It is considered the most dangerous organ-stannic compound, although it is less toxic than other compounds used for the same purpose during the middle of the last century (organic compounds of Hg and Pb, compounds of As and DDT) (Alonso Felipe, 2011).

TBT is capable of causing harmful effects in extremely low concentrations with toxic thresholds in the most sensitive groups, such as phyto-zooplankton and oysters, below 1 ppt, a concentration that is easy to reach in real situations, even in areas away from emission sources. In the sediment, TBT can persist for years, even decades, representing a long-term contaminant deposit that can pose problems as it is relatively weak and reversible.

An example of the persistence of TBT is a study by scientists from the College of Fisheries and Ocean Sciences of the National University of Korea of Chonnam and the Center for Environmental Risk Research of the National Institute of Environmental Studies of Japan. The study was about biocides in water and sediments from three Korean special management marine areas after ten years of the ban on tributyltin. The results show evidence that there is still TBT contamination and that the levels of this biocide in the water exceeded the chronic criteria to protect the aquatic life of seawater in some places. TBT concentrations in sediments at key points such as shipyards exceeded global sediment quality guidelines and represent potential risks to marine organisms. Furthermore, in this study, an extremely high concentration of TBT of up to 2304 ng / g dry weight was found for a sediment collected in a shipyard even 10 years after the prohibition of the use of TBT-based antifouling paint (Hoang et al., 2017).

2.3 From Micro to Macro biofouling: the process of formation

All the vessels and marine structures present a certain degree of biofouling; this includes those whose helmets have been recently maintained and those to whom a new anti-fouling system was applied (IMO, 2011). As frequently happens with the vast majority of solid surfaces that are submerged in water, after a short time being submerged, the hull of a ship is covered with numerous marine organisms if nothing is done to prevent it.

In general, the process of biofouling begins with the adsorption of organic molecules on the newly submerged metal surfaces, which is the development of micro-fouling, then the bacteria, diatoms, and other microorganisms accumulate, attached to an extracellular film of polymeric substances. Such biofilms develop rapidly on surfaces in a matter of hours of immersion, increasing in density and structural complexity as time passes (Zobell & Allen, 1935).

However, the problem of the development of biofouling is a complex issue that involves several stages. From the moment a structure enters the water, it comes into contact with more than 400 organisms that are related to the problem of fouling, which can be divided into microorganisms and macrofouling (Lehaitre, Delauney, & Compere, 2008).

As can be seen in figure 10, the adhesion process of fouling organisms usually considers four main stages:

- The first stage is the adsorption of organic and inorganic macromolecules after immersion: the primary film.
- The second stage is the transport of microbial cells to the surface, and the immobilization of bacteria.
- In the third stage (consolidation), bacterial binding to the substrate is consolidated through extracellular production polymers, forming a microbial film on the surface.
- In the fourth stage, a more complex community is developed with the presence of multicellular species, microalgae, residues, sediments on the surface. After this

stage, larger marine invertebrates such as mussels, barnacles, and macroalgae join the surface, forming macrofouling.

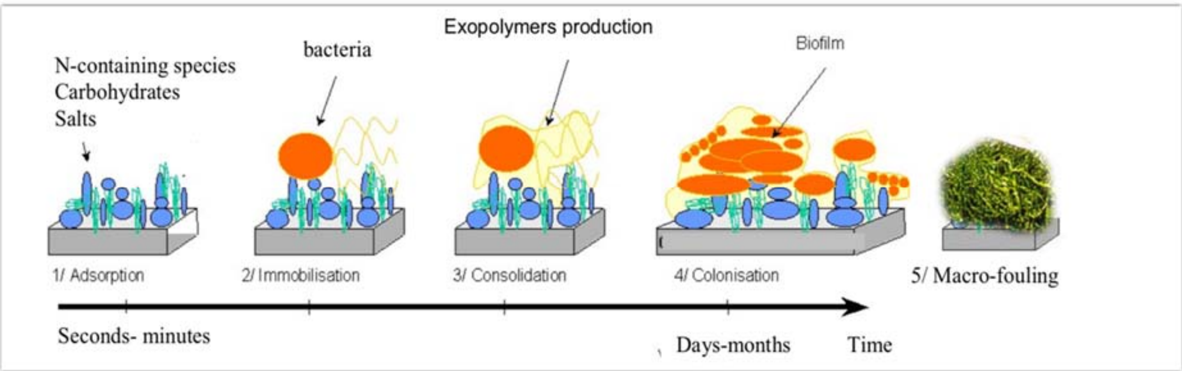

Figure 8 Steps of Biofouling formation

Source: Charaklis, 1990

Other authors such as Rodrigo E. Tun-Che, in their publication on the environmental and economic impact of biofouling, point out that the stage of biofouling formation is a dynamic successional process, which depends both on environmental factors, as well as on the nature and physical characteristics of the substrate. The colonization of new surfaces consists of three consecutive stages, which begin immediately after the immersion with the conditioning stage, where organic molecules such as lipids, proteins and humic substances form a thin layer of macromolecules on the surface of the substrate. Subsequently, bacteria and photosynthetic microalgae precursors of biofilms adhere, in the second stage known as the "microincrustation stage" which is the basis for the formation of biofouling.

Finally, the macroincrustation stage is presented, where the colonization of organisms such as diatoms, larvae of mollusks, spores of algae and protozoa on the biofilm is presented and in a few hours or days the soft macroincrustation can be observed (Holmström, Egan, Franks, & McCloy, 2002).

2.3.1 Conditioning stage.

This stage begins when the surface has direct contact with the water, causing an electrostatic change between the substrate and the macromolecules suspended in the water column, increasing their interactions. Proteins are strongly influenced by the physicochemical properties of the substrate, including electrostatic change, which plays an essential role in the conditioning and adhesion of microorganisms. The changes and the speed at which conditioning is carried out largely depends on the chemical nature of the substrate.

2.3.2 Stage of micro incrustation.

Microbial colonization.

Microbial colonization, on a surface submerged in the aquatic environment, is a phenomenon that occurs in several parts at the same time, where microorganisms seek a place with the conditions of light, temperature, humidity, and flow of nutrients suitable for their growth and development. The marine microorganisms are transported primarily by physical forces such as Brownian movement, electrostatic interactions, gravity, Van-Der-Waals forces, in addition to the impulse of their flagella and cilia that facilitate their movement in the water column and surfaces (Wahl, 1989). Once the microorganisms find the right conditions, the development of a biofilm begins.

Biofilms.

Biofilms are microbial organizations composed of microorganisms that adhere to the surface thanks to the secretion of extracellular polymeric substances, "EPS", and this usually happens in a solid-liquid interface. These microbial conformations present characteristics such as heterogeneity, diversity of microenvironments, antimicrobial resistance and intercellular communication capacity, which makes them difficult complexes to eradicate in the environments where they are established (Betancourth, Botero, & Rivera, 2004).

The development of biofilms begins when the bacteria make a transition from the planktonic state to a lifestyle in which microorganisms are firmly attached to a biotic or abiotic surface (O´toole & Kolter, 1998). Each bacterium undergoes a "reversible fixation" that involves the contact of the cell pole with that of the surface. This interaction is relatively weak and can easily be removed (Hinsa & O´toole., 2006).

This transition is essential to partially regulate the nutritional status in the environment. Eventually, the cell adheres along its axis, this is known as "irreversible fixation," in which the bacterium is firmly fixed to the surface forming a monolayer of cells. After colonizing the surface, the cells undergo phenotypic changes and produce other molecular structures, such as exopolysaccharides. During its growth, biofilms tend to form mushroom-like structures, which proliferate, joined by microorganisms and extracellular polymeric substances. The union of the structures leaves channels of water that penetrate to the base (Wimpenny & Colasanti, 1997), thus facilitating the distribution of nutrients, waste, and carrying planktonic bacteria to be housed in small cavities.

By forming the biofilm, it can have a thickness that varies from a few micrometers to a few centimeters. This variation depends in part on the composition of the medium, the nature of the substrate, the strains present and the time, among other factors. As mentioned above, the thickness of the biofilm is not homogeneous on a surface. Therefore, the content of dissolved oxygen contained in the biofilm varies; this can be seen in Figure 9, which represents a conceptual model of the architecture of a single species biofilm.

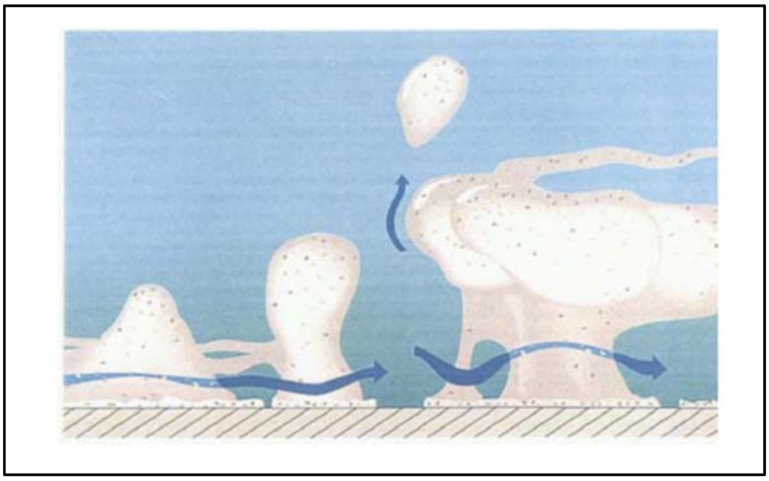

Figure 9 conceptual model of the architecture of a single species biofilm.

Source: Costerton, 1995, Microbial Biofilms Annu. Rev. Microbiol.

2.3.3 Stage of macro incrustation

The last stage of the biofouling takes place after several weeks or months of the immersion of the substrate into the marine environment. Usually, the biofilm developed induces the adhesion of macroorganisms by secretions in the exopolymer matrix. However, some biofouling agents such as bryozoa and polychaetes do not require a biofilm for their adhesion (Wahl, 1989).

The macro incrustation is divided into two phases. In the first phase, organisms such as protozoa, invertebrate larvae and macroalgae spores are embedded in the biofilm, creating a smooth or young macro incrustation. After several weeks, the larvae and spores develop, giving rise to hard or mature macro incrustations where it is possible to observe the variety of mollusks, crustaceans, tunicates and macroalgae that adhere. Macro-incrustation organisms can show rapid growth (serpulids), initially dominating the community, or slow-growing (mussels), which later replace the first encrusting colonizers (Wahl, 1989).

Macro fouling usually represents a greater problem than micro fouling for ships and marine structures due to the fact that they increase the weight and load in a great amount when adhering to the surface. Macro fouling can be of many types, both vegetable and animal and is generally classified as "soft" and "hard". The main characteristic of hard species is that they have a solid skeleton, such as a shell or a calcareous tube (calcareous algae, barnacles, mussels, tubular worms, ...) that protect the body, while soft species have no such protection (sponges, anemones, bryozoans). In Figure 10 it is possible to see a summary of the main organisms belonging to these two categories of macrofouling.

Table I: Main hard and soft marine growths

Hard fouling	Soft fouling
Mussel	Seaweed
Barnacle	Hydroid
Oyster	Soft coral
Tubeworm	Sponge
Encrusting sponge	Anemone

Figure 10 Main hard and soft marine growths. Source: Lehaitre et al., 2008

2.4. Environmental Factors influencing the development of biofouling.

Many factors influence the development of biofouling in ships and the number of organisms that adhere to the hull and other areas. The degree of fouling depends not only on how long the vessel stays in the port or what is its cruising speed but also on the nature of the water in different regions of the world. The influence of various characteristics of seawater such as salinity, temperature, pH, dissolved salts, and oxygen concentration in the incrustation of submerged solid phases is also a relevant factor. Latitude, which influences the average temperature, salinity, and density of the ocean water, affects the degree to which marine organisms are embedded in submerged surfaces. The difference in latitude explains the diversity of fouling in different areas of the world and the reason why the equatorial or tropical regions are more abundant in certain species than other temperate or cold areas (Gabaldón, n.d). Another relevant factor when analyzing the amount of fouling that can be attached to a vessel is the design and construction of the ship, specifically the number of niche areas and the location they have (Strietman & Leemans, 2019).

The problem of biofouling is an issue as old as navigation itself. Since the first navigators put their ships into the water, the organisms began to adhere to their hulls, causing the first problems. In the past, people only looked for solutions that were effective for ship efficiency, first with copper sheets to later go on to the development of paints that used toxic compounds such as TBT. Over time the international community realized that biofouling causes severe problems to the environment due to the transfer of invasive aquatic species that move attached to the hull; It seriously affects the roughness of the hull of ships, which at the same time increases the fuel consumption and the GHG emissions; and finally the solutions created to eliminate biofouling turned out to be a new source of environmental problems due to the toxicity of its components. As a way to address the issues mentioned above, IMO and some countries that were most affected by IAS developed specific regulations that will be described in the next chapter.

3. CHAPTER III: The IMO Framework and selected national instruments related to Biofouling and Antifouling systems

In this chapter, the IMO legal instruments related to biofouling and antifouling systems will be introduced. Besides, some selected national regulations from the United States, New Zeland, and Australia will be mentioned. Further, the inclusion of biofouling on ship energy efficiency and relevant regulations and guidelines will be mentioned in general, e.g., EEDI, EEOI. In addition, more details focusing on SEEMP will be discussed for its importance to the matter of ship energy efficiency. Finally, IMO Biofouling Guidelines will be introduced to recognize its significance and relevance to the legal framework alongside with Glofouling Partnership Project.

3.1 Biocide control and the AFS Convention

As mentioned in the previous chapter of this work, every ship undergoes a process of colonization and encrustation by algae, larvae, mollusks, bacteria, sediments and other marine organisms on its hull subjected to the action of seawater. The process of bioaccumulation reduces its speed, forces it to increase the consumption of fuels to achieve the same previous speeds, producing, additionally, deterioration of the hull paint, blockage of the piping systems, increasing the periodic maintenance and cleaning tasks of the hull, as well as greater emission of toxic gases.

The way in which the shipping industry has been facing such problems in the hull of its ships for decades, is by applying antifouling paints or also called anti-fouling systems, with the specific objective of avoiding or at least reducing this formation process of biofouling. This helps on the one hand to maintain its original design speed, without incurring higher fuel costs, by reducing the resistance of the helmet to water, while preventing the penetration of scale in its paint, improving the protection of the helmet and avoiding the transport of invasive aquatic species in the hull and niche areas of the ship. The preparation of antifouling paints, had been based from the decades of the sixties and seventies, mainly on biocidal metal products polluting the marine environment such as "tributyltin" (TBT), especially "tributyline" (TBT) and "triphenyltin" (TPT), whose use damages the environment, affecting mollusks, fish, cetaceans, seals, otters and even seabirds, none of which, naturally, were the target of its use.

Due to this indiscriminate use of toxic substances and the negative consequences for the marine ecosystem, countries were progressively legislating to limit and prohibit paintings containing certain biocides, for example organic derivatives of tin.

Development of national regulations banning TBT

As an example some initiatives were carried out by countries that banned dangerous biocides and that led or influenced in some way the creation of the AFS Convention.

- In 1982, France banned the use of paints containing more than 3% TBT by weight in boats under 25 meters, after seeing the adverse effects on oyster calves that year (World Health Organization, 1990).
- In 1988, the United States and the United Kingdom adopted the ban on compounds with TBT, followed by more European countries in 1990.
- In 1990, the Committee for the Protection of the Marine Environment issued a worldwide recommendation of the International Maritime Organization to ban TBT. On November 16, 1990, IMO adopted Resolution MEPC 46 “Measures to control adverse impacts associated with the use of tributyltin in antifouling paints”. The resolution recommends that member countries eliminate the use of TBT in antifouling paints in non-aluminum vessels, less than 25 meters in length; encourage the development of alternatives to said product and consider appropriate ways for the possible total ban of TBT compounds in antifouling paints for ships (Alonso Felipe, 2011).
- Other countries such as Japan, New Zealand, and Australia banned the application of antifouling agents containing TBT, and there are currently restrictions for their use in the US, Sweden, Canada, and the Netherlands as can be seen in the Figure 15.

- In 1998 the IMO General Assembly decided that the MEPC had to work on a global legal instrument for the prohibition of TBT. It was decided that the ban should be effective in 2003 for the use of TBT in paints, and in 2008 for ships treated with those paints.

Regulations of use of organotin-based antifoulants in various countries

Regulations	USA	Canada	Australia	New Zealand	France	UK	Holland Ireland	other EU countries	Sweden*	other non-EU	South Africa
Vessels <25m: all organotin-based antifouling coatings prohibited; exemptions for aluminum structures.	○	○			○						
Vessels <25m: all organotin-based antifouling coatings prohibited; no exemptions for aluminum structures.			○								
Vessels <25m: TBT-based antifouling coatings prohibited; no exemptions for aluminum structures.							○	○	○	○	○
All antifouling products containing triorganotins banned on vessels <25m, and on fish-farming equipment.						○					
Vessels >25m: TBT antifouling available only in 20l containers.							○	○			○
Vessels >25m: low release rate(<4μg TBT/cm²/day) permitted.	○	○							○		
Vessels >25m: low release rate(<5μg TBT/cm²/day) permitted.			○	○							
All antifoulants must be registered.	○	○	○	○		○	○		○		○
TBT paints can only be applied by certified operator.	○										
All antifoulants registered as pesticides, sale and use must be approved by Advisory Committee on pesticides.						○					
Triorganotin paints only sold In drums of 20l or more; must contain <7.5% total tin in copolymers or 2.5% total tin as free tin.						○					

Figure 11 Regulations of use of organotin-based antifoulants in different countries.

Source: Paper Submitted by Japan to MEPC 41/INF.3

3.1.1 International Convention on the Control of Harmful Anti-fouling Systems on Ships – the AFS Convention

As a result of the different initiatives created for the prohibition of TBT, the International Maritime Organization drew up the "International Convention on the Control of Harmful Anti-fouling Systems on Ships" (AFS Convention), adopted on October 5, 2001, and which entered into force internationally on September 17, 2008 , one year after it was ratified by a minimum of 25 States whose combined merchant fleets represented almost 38.1% of the gross tonnage of the merchant marine world. The purpose of the convention is to reduce or eliminate the unfavorable effects of some antifouling systems, widely used as a biocide in ship hull protection paints (IMO, 2008).

The AFS Convention is one of the most recent agreements and the most important points are the following:

- Applies to any vessel flying the flag of a member state and also to those flying a foreign flag but making a stopover in a port of a member state that has adopted the AFS agreement.
- Warships and ships owned by a Member State or providing government services are exempt from complying with the requirements of the Convention.
- Depending on the size of the vessel, periodic examinations and certificates are required.
- For ships with a gross tonnage equal to or greater than 400, it must be subject to recognition and obligation to have the AFS certificate in force.
- Ships of 24 meters in length and less than 400 gross tonnes must carry a declaration of conformity with the provisions of the AFS Convention. For vessels of less than 24 meters in length, they are exempt from certificates and acknowledgments.
- The parties to the AFS Convention undertake to ensure that, as of January 1, 2003, all their vessels do not apply or reapply organotin compounds which act as biocides in antifouling systems. In addition, the parties guarantee that, prior to January 1, 2008, ships should also not carry such compounds on their hulls

or external parts or surfaces, or should wear a coating that forms a barrier to such compounds leaching from the underlying non-compliant antifouling systems (Jackson, 2008).

- The Convention also requires that the waste from the application or removal of TBT-based paints must be handled ecologically and safely, and that ships must be inspected and certified in accordance with the regulations in annex 4 of the agreement.
- One of the most important points of AFS Convention is contained in Article 6, which allows the prohibition of future antifouling systems that represent a threat of serious or irreversible damage to the marine aquatic environment and/or human health (IMO, 2008).

The AFS Convention benefits both the states parties and the shipping industry, while helping to care for the marine environment and the health of people by controlling the toxic substances found in antifouling paints.

For the parties to the AFS Convention they can benefit from: standardized application of controls on antifouling paints on all ships, both domestic and foreign, entering ports, shipyards or terminals on the high seas under their jurisdiction. Parties can also exchange information about new research and development of antifouling technologies, share practical experiences related to the control of harmful antifouling systems. On the other hand, the shipping industry will only have to worry about a single uniform international regime that deals with antifouling systems instead of having to deal with a large number of individual actions and regulations of each country.

3.2 Inclusion of Biofouling in Ship Energy Efficiency instruments by IMO

As previously stated, biofouling has detrimental impacts on roughness of the hull, and therefore fuel consumption increase which ultimately increase GHG emissions. Consequently, to reduce fuel expenses and GHG emissions, the IMO has considered the inclusion of hull cleaning in its regulations related to ship energy efficiency. To respond to the international community to reduce GHG emissions, the IMO started discussions on the topic in 1997 after the Kyoto Protocol. IMO negotiations led to the adoption of MARPOL Annex VI chapter 4 on Energy Efficiency Regulation for ships (Baumler et al., 2014). In this chapter the instruments that have been introduced by IMO regarding the enhancement and reduction of GHG impact will be introduced, in addition to showing their importance and whether they are directly or indirectly tackling the issue of biofouling and GHG. Figure explains the chronological events started at IMO in 1997 regarding GHG and the ships contribution with more focus on introducing legal and practical means to reduce the harmful emissions.

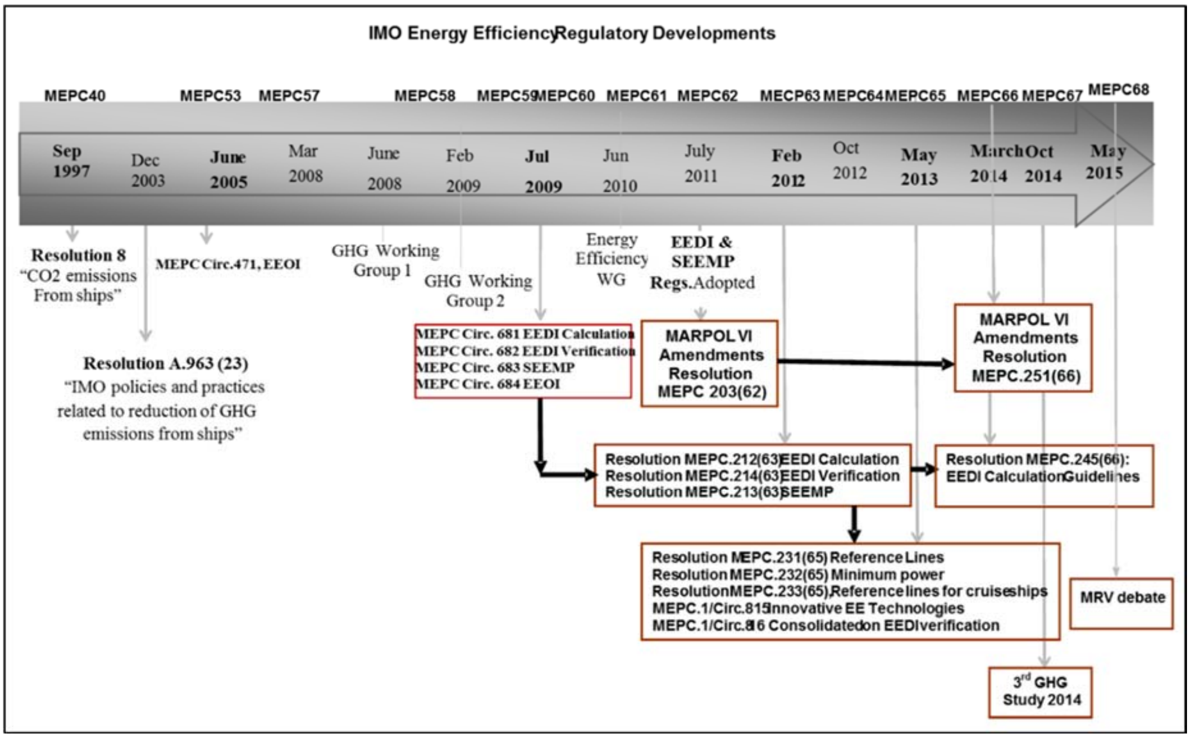

Figure 12 IMO activities in chronological order regarding GHG control.

Source: IMO Energy Efficient ship Operation

To have better understanding of this chronology of events a brief explanation of the major events are necessary to be mentioned:

- **1997:** The IMO started the GHG emissions from ships debates.
- **2000:** The very first study if GHG emissions from ships was carried out .

- **2003:** IMO assembly has adopted the resolution A.963(23) on "IMO Policies and Practices related to the Reduction of Greenhouse Gas Emissions from Ships."
- **2005:** The first draft on the Energy Efficiency Operational Indicator (EEOI) was published.
- **2009:** Drafts about the voluntary use of (EEOI), Energy Efficiency Design Index (EEDI),and Ship Energy Efficiency Management Plan (SEEMP) were published and circulated. Further in the same year, the second IMO GHG study was published.
- **2011:** The mandatory regulations of EEDI and SEEMP were adopted and came into force in 2013.
- **2013:** Debates started at IMO on further energy efficiency measures, focusing on "IMO Data Collection System".
- **2014:** The third IMO GHG study was published.
- **2015:** Debates on "Data Collection System" continued.

Moreover, it is important to address the new established regulations in Chapter 4 of MARPOL Annex VI. This set of regulations were adopted in 2011,covering operational and designing measures (MEPC(62), 2011). These regulations are :

- Regulation 19 - Application
- Regulation 20 - Attained EEDI
- Regulation 21 - Required EEDI
- Regulation 22 - SEEMP
- Regulation 23 - Promotion of technical cooperation and transfer of technology

Figures 13 and 14 shows the applicability of these measures with respect to ship's profile whether at the design stage or operational (new ship and existed ship):

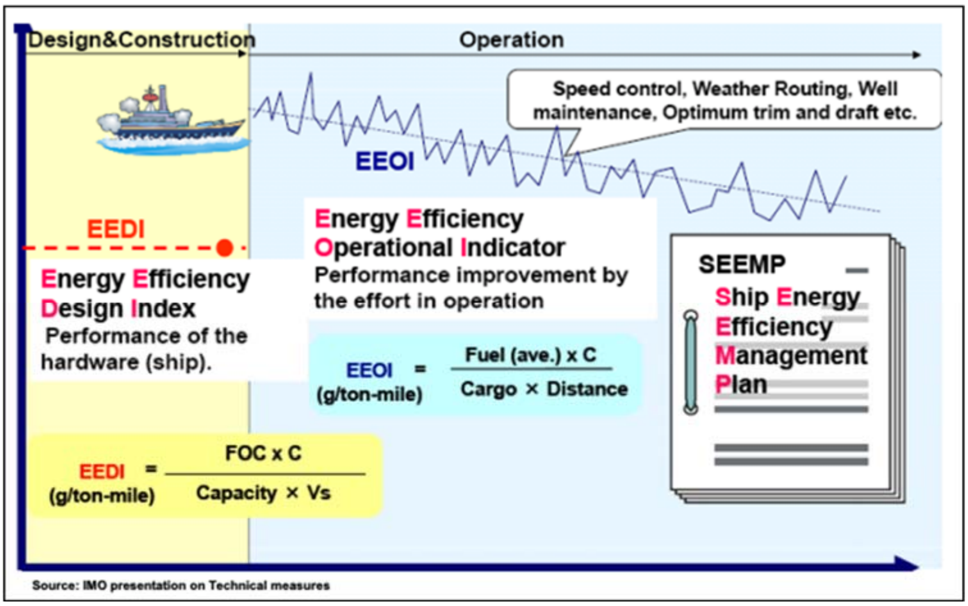

Figure 13 Energy efficiency regulations for both stages design and operation

Source: IMO, Energy Efficient Ship Operation

As shown in Figure 13, EEDI measures are implemented at the design and construction level In addition, EEOI which is an important performance indication is carried out at the operational level. Further, SEEMP measures are carried out during the operational level.

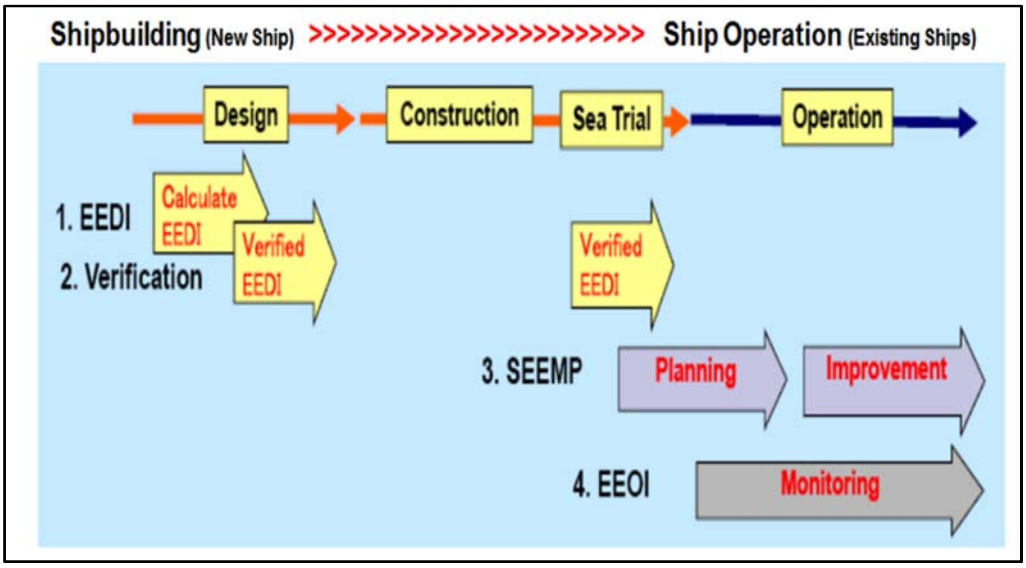

Figure 14 Energy efficiency regulations implementation stages

Source: IMO, Energy Efficient Ship Operation

Figure 14 explains each measure implementation period according to the ship situation. For instance, EEDI calculation and verification are carried out for new ships; on the other hand, SEEMP and EEOI during ship operations.

3.2.1 EEDI (Energy Efficiency Design Index)

EEDI is a technical measure where this measure according to MARPOL Annex VI Chapter 4 should be applied to every applicable new ship. However, EEDI is a non-prescriptive performance mechanism which gives the choice to the industry to decide the technology used to design certain ships as long as it is achieving the energy efficiency level in regulations 20 and 21 (Hughes, 2013). Despite not having a direct measurable impact on EEDI, new hull design reduces the impact of niches that may be related to enhanced energy efficiency. Moreover, the EEDI impact could be more related to facilitating hull cleaning operations.

3.2.2 SEEMP (Ship Energy Emergency Management Plan)

SEEMP is an operational measure introduced by IMO to tackle the issue of GHG, besides, the enhancement of ship energy efficiency. Moreover, this measure has a direct impact on the improvement of ships' energy efficiency as indicated in the 2012 Guidelines for the Development of a Ship Energy Efficiency Management Plan (SEEMP) (IMO, MARCH 2 ,2102). MARPOL Annex VI regulation 22 mentions that each ship should keep on board a ship specific SEEMP, which could form part of the Safety Management System (SMS) of the ship. Moreover, the SEEMP should be improved according to guidelines adopted by the IMO (Baumler et al., 2014). Further, the SEEMP framework should work according to the improvement cycle :

- Planning
- Implementation
- Monitoring
- Self- evaluation

The IMO Guidelines provide details regarding the above mentioned steps and how they could be developed (MEPC.282(70), 2016). More details regarding the

Guidelines of the development of SEEMP will be provided to clarify their direct impact on ship energy efficiency.

As IMO became more concerned about the GHG emissions and the impact on the environment, it became clear that more ship efficiency means less harmful emissions, Therefore, all interested parties pushed forward the appeal to reduce ships' emission and enhance efficiency. Consequently, the SEEMP measure is an energy management tool to assist ship owners and operators in managing their ships' energy efficiency. SEEMP is basically a ship specific document containing identified measures for ship owners regarding the improvement of the ship efficiency. In the same context, SEEMP was been introduced as an operational measure according to the 2012 Guidelines for the development of a ship energy efficiency management (SEEMP) These Guidelines have been developed to assist with the preparation of Ship Energy Efficiency Management Plan (SEEMP) that are required by regulation 22 of Annex VI of the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto (MARPOL 73/78) (IMO, MARCH 2 ,2012). SEEMP is divided in to two parts. The first part lists the specific measures that were identified by the ship owners besides the responsible persons for each. For Example:

- Fuel efficient operations.
- Routing and weather systems.
- Engine performance.
- Draft and trim optimization
- Propeller and hull cleaning/inspection: This measure in SEEMP points to the importance and the relation of biofouling to the ship energy efficiency. The cleaner the hull and propeller are, the more efficient the ship is. Unlike the EEDI measure, which is more technical and related to the design of the ship, SEEMP facilitates the hull cleaning operation in the design stage rather than in the operational stage. Figure 15 presents examples of SEEMP energy efficiency measures.

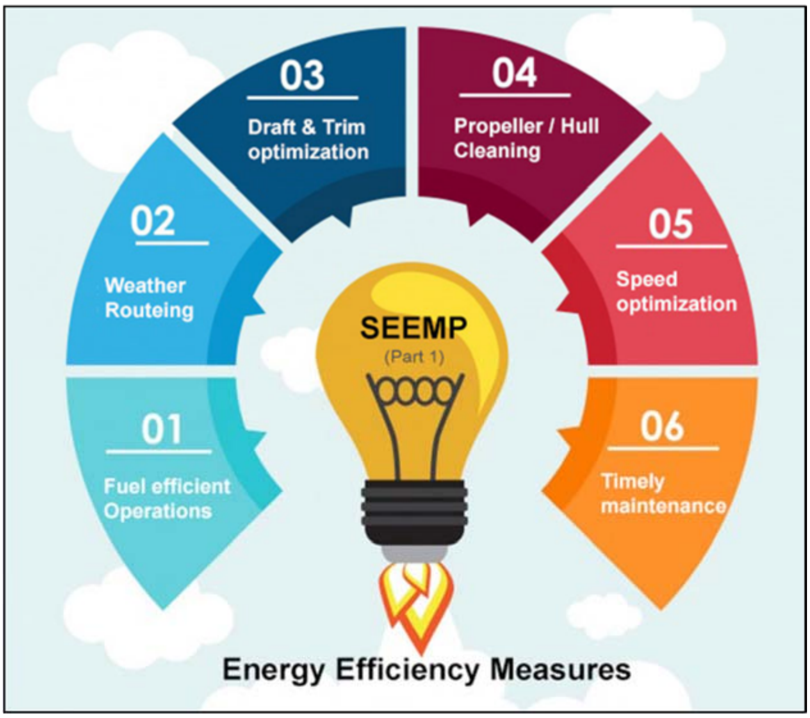

Figure 15 SEEMP Measures.

Retrieved from https://www.myseatime.com/blog/detail/ship-energy-efficiency

The second part of SEEMP, which according to Resolution MEPC.282(70), is related to the data collection where MARPOL Annex VI, regulation 22A requires that all ships above 5000 GT from 2019 calendar year has to provide IMO through Flag States the following data:

- Type of fuel consumed.
- Amount of fuel consumed.
- The voyage distance.
- Hours underway
- The SEEMP part II basically provides guidelines on how this data could be collected.

For example:

- Method using bunker delivery notes (BDNs).
- Method using flow meters.
- Method using bunker fuel oil tank monitoring on board.

3.2.3 EEOI (Energy Efficiency Operational Indicator)

EEOI is an element of IMO regulatory framework that acts as an indicator of the ship energy efficiency performance; however, this measure according to IMO Guidelines (MEPC.1/Circ.684, 2009) is for voluntary uses whereby this key performance measures and indicates the ship energy efficiency by calculating the actual fuel consumption and actual voyage distance besides cargo carried by the ship. However, this particular measure is concerned about how efficiently the ship is operated. In contrast, EEDI is more related to how efficiently the ship is designed.

3.2.4 International Energy Efficiency (IEE) Certificates for Ship

According to IMO regulation [MEPC 203(62)] an IEE certificate must be issued to all applicable ships above 400GT engaged in an international voyage and entering other parties' jurisdictions. Moreover, this certificate should be valid the entire life of the vessel unless there are major conversions or changes in the ship registration.

3.2.5 Promotion of Technical Co-operation and Transfer of Technology

MARPOL Annex VI regulation 23 mentions that maritime administrations should with other international bodies in cooperation with IMO provide assistance and support, especially to developing countries. Furthermore, maritime administrations should actively provide assistance with developing countries according to their request whether technical or information exchange, in order to help them implement the energy efficiency regulations (Resolution MEPC.229(65), 2013).

3.2.6 Data collection system for fuel oil consumption of ships

The IMO Resolution MEPC.278 (70) amendments to MARPOL Annex VI, Regulation 22A on a Data Collection System (DCS) came into force on the 1 March 2018, which requires the ships of 5000GT and above to record and report the fuel oil consumption to flag states, then transfer these data to the IMO after the flag states' approval (Resolution MEPC.278(70), 2016).

In summary, the term ship energy efficiency contains four parts that ensure the enhancement of ships' energy efficiency besides measures to improve the hull smoothness and reduce the accumulation of fouling, thus reducing the impact of GHG due to ships emissions. These four parts are as follows: EEDI, which is related to the improvement of the ship design to reduce its CO2 emissions per ton-mile of the work done by the ship. SEEMP, which is a specific plan that contains specific measures implemented by the ship operator or owner to improve the ship energy efficiency. EEOI is a voluntary monitoring tool provided by IMO to measure actual CO2 emissions per ton-mile of the ship's transport work. IEE is an endorsement means to ensure the ship compliance with applicable international energy efficiency measures.

3.3 IMO Biofouling Guidelines

Biofouling is a detrimental issue to the environment as the transference of aquatic species by ships will introduce the invasive species to new marine locations in which they will affect the ecological system. Further, the transfer of invasive species can threaten the fresh water, animal life as well as cultural and economic activities. Even when the problem of IAS is not as visible as other environmental problems, measures to minimize this issue shall be undertaken to protect the environment. The issue of transferring aquatic invasive species by ships' hull (biofouling) was firstly brought formally to IMO's attention in 2006. The following year, MEPC handed the task to the sub-committee on Bulk Liquids and Gases (BLG) to develop guidelines on biofouling, and after successive work by the sub- committee the Guidelines were adopted in 2011 by MEPC (IMO, 2011a). Moreover, IMO has published the Biofouling Guidelines, in order to minimize the impact of transferring invasive species by ships' hull through recommendatory measures introduced by the Guidelines to manage and control the biofouling (Resolution MEPC.207(62)) (IMO, 2011c). The Biofouling Guidelines provide practical guidance solutions for maritime engaged parties to minimize the impact of biofouling , for instance flag states, port states, ship building yards, dry docks, and all other interested stakeholders (IMO, 2011). Further, IMO has provided a guidance to evaluate the Biofouling Guidelines by member states and observers who wished to gather information for future developments. This guidance shows the measures that can assist in applying the evaluation in the most effective way (IMO, 2013).

3.3.1 Biofouling Guidelines Objectives

The objective of the Guidelines is to give the most effective measures to all parties engaged in the maritime industry to minimize and control the impact of transferring the invasive species from ship's hull. The Guidelines introduce practical measures which help the ship's submerged part to reduce the accumulation of fouling, starting with recommendations related to the installation of anti-fouling systems besides the management of cleaning the hull. All these practical measures are intended to achieve the reduction of carrying marine species that affect the marine environment and improve the operational cost which is related to ships' efficiency due to fouling growth on the hull (IMO, 2011).

3.3.2 Biofouling Management Plan and Record Book

Biofouling Management Plan

The Biofouling Management plan is recommended to be carried on all ships. This plan provides effective procedures for biofouling management. Moreover, the Management Plan could be a stand - alone document or partly or fully integrated within the ship's operational manuals. Further, the Management Plan covers the following areas: details of antifouling systems with those related to niche areas, the susceptible locations of biofouling on the hull with the maintenance schedule, details of recommended operational conditions suitable for antifouling systems, relevant details of the safety of the crew and the required documentations on verifying processes recorded in the book. In addition, the Biofouling Management Plan should be updated as necessary (IMO, 2011).

Biofouling Record Book

It is recommended that each ship should have a record book, whose objective is to record each measure undertaken by the ship. The record book can assist the ship owner and maritime administration and the interested stakeholders to assess the measures efficiently. It is recommended that the record book be kept onboard the ship for its whole life. The record book should record the following information: the details of antifouling system practices used, the dates and locations of dry docking, the date and location of in-water inspections, the dates and information of the maintenance and inspection of internal seawater cooling systems, details of when the ship has been operating out of it is regular operating areas and also the period and location where if it was lid-up or inactive (IMO, 2011b).

3.3.3 Antifouling System Installation and Maintenance

Antifouling systems is the primary means for the prevention of biofouling on the submerged portion of the vessel, in addition to the niche areas . Antifouling systems can be applied as coating for exposed surfaces while the biofouling resistance materials can be applied for pipelines. Moreover, marine growth prevention systems (MGPSs) are measures applied for sea chests and internal seawater cooling systems (IMO, 2011).

3.3.4 In Water cleaning , Maintenance and Inspection

Although antifouling systems are effective and their prevention of the accumulation of biofouling, the chance of undesirable biofouling attachments are highly possible to occur. Therefore, inspection measures are advisable to be carried out to maintain the hull and niche areas as clean as possible (IMO, 2011).

3.3.5 In-Water Inspection of Ships

In water inspection is a practical measure that can assure the situation of antifouling systems by inspecting the biofouling status and antifouling condition. The inspection should be carried out periodically as a routine surveillance to the hull performance (IMO, 2011).

3.3.6 In-Water Cleaning and Maintenance

The in water cleaning and maintenance process is a very important part of biofouling management where it can be dangerous to the environment. However, the accumulation of biofouling can affect the ship efficiency by increasing the fuel consumption besides increasing the impact of GHG due to the CO_2 emissions (Edmund Hughes, Technical Officer, Marine Environment Division, IMO, 2013). It is recommended that states carry out in water inspection to improve the ship efficiency and reduce the harm of emissions to the environment besides decreasing the impact of transferring the invasive aquatic species that accumulated as macrofouling and microfouling. Hence, such procedures should be carried out with considerations to the residues which could affect the marine environment where the operation was executed. For that reason, it might be appropriate to put through a risk assessment to avoid environmental issues related to the cleaning operation (IMO, 2011).

3.3.7 Design and Construction

The ship design can be effective and comprehensive minimizing the risk of biofouling accumulation on the ship hull. Moreover, during the process of building and designing the following points should be considered (IMO, 2011):

- The small niche areas should be excluded as far as practical possible, apart from making them easy in terms of accessibility for inspection and cleaning and also to apply antifouling applications.
- Rounding the ship as much possible for more anti fouling painting effectiveness, besides improving the hangings for easy diving accessibility.
- Provide the ability of blanking off the sea chest and other free flood areas, for treatment and cleaning.

3.4 Recreational craft

The IMO in its pursuit to minimize the impact of the transference of invasive species by ships established the Biofouling Guidelines. Therefore, all type of ships were included in these particular guidelines. However, IMO has considered the same issue with different type of vessels, namely recreational craft that are less than 24 meters in length. Recreational craft are prone to carrying invasive species and cause the same detrimental impact to the marine environment. Therefore, IMO introduced a specific guidance regarding recreational craft “Guidance for minimizing the transfer of invasive aquatic species as biofouling (hull fouling) for recreational craft” providing information consistent with the Biofouling Guidelines (IMO, 2012).

Influencing factors of biofouling amount on recreational craft

Recreational craft can have some fouling attached to their body despite the fact that they were recently cleaned or anti fouling paints had been applied. These factors are:

- The age, type of antifouling coating and the cleaning practices.
- The operational profile including the speed, time, locations, in addition to where the craft is normally kept. For example, on land or marina.
- Design and construction specially the susceptible places to biofouling e.g. rudder and propeller.

To sum up, the biofouling on recreational craft could be minimized by following the measures in the guidance for owners and operators. Moreover, an appropriate antifouling coating besides regular maintenance is the best practice to minimize the chance of transferring the fouling via recreational craft.

3.5 GloFouling Partnership Project

The GloFouling project is an initiative of IMO in collaboration with the United Nations Development Program UNDP and the Global Environment Facility (GEF), whose objective is to protect the marine environment from the impact of transferring IAS with the associated risk of GHG emissions from ships. This project began in 2011 under the GloBallast Program (Glofouling, 2011). Moreover, the main objective of this initiative by IMO is to build capacity in developing countries for the implementation of IMO Biofouling Guidelines and other relevant guidelines aiming to manage and control the environmental impact of IAS. Further, there are key outputs which are institutional outputs. For instance, there are national and international strategies; awareness outputs by raising the awareness of invasive species and biofouling through all available aspects; technical outputs e.g. reports on the GHG; the industry, such as the global industry alliance and capacity involving gender empowerment activities (Glofouling, 2011).

3.6 Selected national regulations related to biofouling on ships.

For the present work, three countries were selected, which have specific regulations on biosafety and have been greatly affected by the introduction of invasive aquatic species. In the case of Australia and New Zealand, these countries have been leaders in introducing control measures to manage the risks of IAS, and raised concerns about the risks of biofouling in 2005 at the 54th session of the IMO MEPC.

IMO and the international community have recognized the risk posed by invasive aquatic species for the marine environment, whether transported in ballast waters or on the hull of the vessel attached as biofouling. As a result of the existing concern is that the Ballast Water Management Convention was adopted and entered into force on September 8, 2017 (DNV, 2017). However, biofouling management is not considered within the BWM Convention since it is not part of the scope. The latter represents a problem because biofouling is a decisive factor when it comes to the transfer of aquatic species, and even some scientific studies suggest that 70-80% of the introductions of IAS are the product of biofouling (Urdahl, 2017); however, its regulations still remain voluntary.

Although it is true, at the moment there is no strict international legal framework in relation to the introduction of IAS through biofouling, the issue has taken on greater importance both in the IMO and in the countries affected by this problem, which has led to the creation of new regulations both local, regional and international. Countries like the United States, New Zealand and Australia have developed their own stricter regulations to combat and protect their territory from this serious problem that has brought economic, health and environmental detrimental consequences.

Examples of the new regulations required by these countries are the following:

- The United States, through its Coast Guard, demands to keep on board a Biofouling Management Plan, since June 21, 2012. In addition, the State of California established the Invasive Marine Species Program in 1999, which was reauthorized and extended in 2003 by the Invasive Marine Species Act. The program aims to address the threat of the introduction of invasive species in vessels that arrive in the ports of California (California State Lands Commission, 2019).

- Australia, since 2009, has developed voluntary guidelines to control biofouling in pleasure boats, non-commercial vessels, commercial fishing vessels and also in the oil industry, including oil exploration and production platforms and commercial vessels. Since 2013 the aquaculture industry has also been considered by the guidelines; however, all these measures are voluntary, and the creation of stricter regulations for biofouling is under evaluation (DNV, 2017).
- In order to protect its marine environment and its aquaculture industry against invasive species, New Zealand tightened its biofouling regulations for ships entering its waters. Since May 2018 all ships that reach their jurisdiction must have a clean hull or comply with what is established in the biofouling management best practices. If the vessel is evaluated as having more biofouling than allowed, the ship's documents will be inspected concerning the operational history and maintenance records of biofouling, and in some cases, the inspection of the hull by divers is necessary. If the biofouling exceeds the allowed limits, then the entrance will be restricted to New Zealand, the itinerary will be reduced within the country, or the hull will be requested to be cleaned by an approved treatment or in less than 24 hours by a country-approved provider (Revista de Ingeniería Naval, 2018).

3.6.1 Marine Invasive Species Program - United States

The United States and specifically the state of California and the West Coast have been greatly affected by the problem of invasive aquatic species (U.S. Fish & Wild Life Service, 2012). To deal with this problem, the State of California, through its legislation, established the Marine Invasive Species Program in 1999 with the objective of addressing the threat of the introduction of IAS in ships arriving at the ports of California. The Program aims to be a leading global program to reduce the risk of introducing IAS into California's waters and ports through the development and implementation of ballast water and biofouling management strategies and policies; the use of the latest technologies available for the control of invasive species and agreements with the different actors involved in the maritime industry to improve awareness of the problems caused by IAS (California State Lands Commission, 2019). The regulations apply to vessels that are 300 gross registered tons or more and capable of carrying ballast water.

In addition to the biofouling regulations in California, the United States regulates the management of biofouling by federal law although these federal regulations are not as detailed as the biofouling regulations in Californa. The US Coast Guard requires that all ships rinse the anchors and anchor chains, and also remove dirt from the hull, pipes, and tanks regularly. Figure 16 shows a summary of the regulation related to biofouling in California.

California, United States (US)

Title:	Biofouling Management Regulations to Minimize the Transport of Nonindigenous Species from Vessels Arriving at California Ports (Article 4.8)
Effective:	1 October 2017
Application:	Vessels of 300 GRT or more that arrive at a California port and carrying, or capable of carrying, ballast water

Key requirements:

- From 1 October 2017, the *Marine Invasive Species Program Annual Vessel Reporting Form* (SLC 600.12) must be filed at least 24 hours prior to a vessel's first arrival in any given calendar year at a Californian port. This can be done using the online Reporting Form Web Application at: https://misp.io. Vessels that have called at a Californian port in 2017 prior to 1 October are not required to submit the new Annual Vessel Reporting Form for 2017.

  The previous *Ballast Water Treatment Technology Annual Reporting Form*, *Ballast Water Treatment Supplemental Reporting Form*, and the *Hull Husbandry Reporting Form* are no longer valid.
- From 1 January 2018, after a vessel's first regular scheduled dry docking after this date, or upon delivery on or after this date, a vessel-specific Biofouling Management Plan and Record Book consistent with the requirements of the IMO Biofouling Guidelines must be carried onboard and the vessel's wetted surfaces managed in accordance with the plan. The regulations emphasise the increased biofouling risk of vessels that undergo an extended residency period, i.e. remain in the same location for 45 days or more.

Figure 16 Summary of California´s Biofouling Management Regulation.

Retrieved from http://www.gard.no/web/updates/content/24305557/biofouling-moves-up-the-regulatory-agenda

3.6.2 Craft Risk Management Standard for Biofouling (CRMS) - New Zealand

Craft Risk Management Standard (CRMS) entered into force on May 15, 2018, and its objective is to establish the requirements for the management of biofouling risks through ships entering the territorial waters of New Zealand. The Ministry for Primary industries (MPI) is responsible for monitoring and implementing the program, which is mandatory as of May 2018. In the four years before the entry into force of the CRMS, there was a voluntary "clean hull" protocol. Today, all ships that do not meet the minimum requirements for cleaning the ship's hull must leave the ports and territorial waters of New Zealand (Irving & Mc Carthy, 2018).

CRMS specifies the measures that operators must take to ensure that the hull of their vessels is clean before it reaches the territorial waters of New Zealand. Some measures are:

- Demonstrate that the cleaning of the hull was done in less than 30 days before arrival;
- Demonstrate evidence of hull maintenance using best practices;
- Book an appointment in an MPI approved facility to carry out a cleaning/water treatment within 24 hours of arrival at the port in New Zealand.

To demonstrate compliance with the New Zealand regulation, ships entering their ports must carry on board and be able to present to an MPI inspector an antifouling certificate and a biofouling management plan; reports of the most recent cleaning of hulls and niche areas; contingency planning records in clean hulls; biofouling management plan and a biofouling record book (Irving & Mc Carthy, 2018).

New Zealand

Title:	Craft Risk Management Standard for Biofouling (CRMS)
Effective:	15 May 2018
Application:	Vessels that will anchor, berth or be brought ashore in New Zealand after a voyage originating outside New Zealand's territorial waters.

Key requirements:

- From 15 May 2018, vessels must arrive in New Zealand with 'clean hulls'. For vessels staying up to 20 days and only visit designated ports, a 'clean hull' means a slight amount of biofouling: slime layer, goose barnacles, and up to 5% cover of early biofouling depending on the area fouled. For vessels staying longer than 20 days or visiting places other than the designated ports, 'clean hull' means no biofouling apart from a slime layer and goose barnacles.
- The regulations provide three options on how to meet the 'clean hull' requirement: a) cleaning before entry (carried out less than 30 days before arrival in New Zealand or within 24 hours after arrival); b) continual maintenance by use of best practices such as those detailed in the IMO Biofouling Guidelines; or c) application of approved treatments.
- To demonstrate compliance, vessels arriving in New Zealand will be required to submit information about their biofouling management practices. For vessels relying on continual management, this includes a biofouling management plan and record book consistent with the IMO Biofouling Guidelines.

Figure 17 Summary of CRMS in New Zealand.

Retrieved from http://www.gard.no/web/updates/content/24305557/biofouling-moves-up-the-regulatory-agenda

3.6.3 The Biosecurity Act 2015 - Australia

Australia is a country that has one of the strictest biosafety regulations in the world to reduce the risks of introducing pests or diseases into its territory. The Biosecurity Act 2015, began on June 16, 2016, and aimed to ensure that no disease or plague from abroad can cause damage to the health of humans, animals, plants, or the environment (Australian Government, 2019). To achieve this, the Biosecurity Act includes requirements that affect the handling of goods, people, and ships entering Australia. However, the regulations contained in the Biofouling Act does not expressly mention biofouling although as it has been seen in previous points, it represents a significant risk for the introduction of invasive aquatic species.

Regarding the control of biofouling that can enter ships that arrive at its ports, Australia has developed the National Biofouling Management Guidelines, which aim to help the maritime industry and stakeholders to control the risk of biofouling. The problem with the guidelines is that because they are voluntary, they are not binding and only give recommendations on the best practices for the application, maintenance, removal of antifouling coatings. They also include recommendations on in-water cleaning and maintenance of mobile structures in order to minimize the risk (Legal Update, 2017).

Australia

There are currently no legislative requirements expressly dealing with biofouling for vessels entering Australian waters. The Biosecurity Act 2015 does, however, provide for biosecurity measures to be taken in relation to vessels if the level of biosecurity risk associated with them is unacceptable.

Under the Australian Maritime Arrivals Reporting System (MARS), government officials will be provided with sufficient information to determine, prior to a vessel's arrival, the potential biosecurity threat presented by the vessel, including threats due to possible biofouling. This allows inspections to be targeted and may potentially provide a basis for banning a vessel from making a port call.

Figure 18 Australian Biosecurity Act 2015.

Retrieved from http://www.gard.no/web/updates/content/24305557/biofouling-moves-up-the-regulatory-agenda

In other words, the protective antifouling paints are essential for ship's hulls to improve its performance and to reduce the accumulation of biofouling. Hence, TBT paints have detrimental impacts to the environment where it is highly toxic; therefore, it could lead to killing the local aquatic systems. After, the international community has pushed forward to combat this issue globally by introducing the AFS convention that includes measures to mitigate the adverse effects of antifouling paints, in particular, TBT based paints. Moreover, IMO has considered the issues related to the ships energy efficiency and GHGs, for their importance for all stakeholders, to improve the performance of the ship and reduce the impact of pollution through chain of tools; for example, EEDI, SEEMP. Later, in the coming chapter, the current technologies of antifouling systems which comply with the regulatory framework will be revised.

4. Chapter IV: Antifouling systems

In this chapter dedicated to antifouling systems, a brief historical review of the evolution of the technologies used to avoid the adhesion of organisms to the hulls of ships will first be made, starting with the copper sheets to the paints and other systems used today. Subsequently, the importance of paints using TBT and the evolution of new technologies after the prohibition of this toxic compound will be mentioned.

Following the antifouling paints topic, the various classifications of paints and their mechanisms of action, both using biocides and without the use of biocides, will be described. Finally, new antifouling technologies will be introduced , and a study by New Zealand to determine the best type of paint for each type of ship will be announced.

4.1 Evolution of Antifouling systems

According to the International Convention on the Control of Harmful Anti-fouling Systems on Ships, an anti-fouling system is defined as "a coating, paint, surface treatment, or device that is used on a ship to control or prevent attachment of unwanted organisms"(IMO, 2001).

The first known use was the one used by the Phoenicians in Greek and Roman vessels to give extra speed without knowing its anti-fouling properties (Stephens, 1952). The first anti-fouling surface that received great recognition was the copper coating.

Despite its use between the twelfth and fifteenth centuries on rooftops, it was not until the seventeenth and eighteenth centuries that these copper elements began to be used on ship hulls as anti-fouling. As of 1728, it began to be used as a new method of preserving the hull of important vessels such as the frigate H.M.S. Alarm, in which the copper cladding was used as an experiment to check the conservation of the hull because of the problem of the embedding of worms due to the terrible conditions on the return of his trip to the Indias (American Neptune, 1941). Despite being the best known antifouling method at that time, it was not perfect, because one of its drawbacks was the uncertainty of its functions as an antifouling since it did not work the same in all cases and its corrosion against iron was a problem. The placement of copper plates that protected the submerged part of the ships was the standard method to avoid fouling in those years until the naval industry began using iron hulls, which caused the copper to cease to be used as an antifouling due to its corrosive action for iron (Rodriguez, 2013).

Iron hulls emerged in the industry at the end of the 18th century, and during its first years of use, there were different problems associated with galvanic corrosion, due to the use of copper coatings. After ceasing to use copper as a coating, different metal cladding technologies began to be investigated that had similar anti-fouling properties but without the problem of corrosion on the iron hull. Zinc began to be used as a substitute, and the results were good enough in terms of fouling prevention; however, it became brittle and wasted away too fast, which was not profitable.

One of the significant consequences of the use of ships with iron hulls was the interest in finding compositions that eliminate fouling without causing corrosion. As a result of the interest in the development of new technologies, antifouling paints were created that replaced the copper coatings as antifouling.

4.2 Antifouling coatings used for the efficiency enhancement.

The first paint registered as antifouling protection is from 1625 when William Beale patented a paint composed of iron powder, cement and a copper compound. Later in 1670 Howard and Watson patented a paint composed of tar and resin in a beeswax barn, turpentine oil and lacquer dissolved in alcohol (Stephens, 1952a).

From 1835, and as a result of the problems caused by galvanic corrosion, attention began to focus on antifouling paints. The production of paints increased rapidly in number. In1865 more than 300 patents were already available only in England for antifouling paints (Stephens, 1952).

The trial and error method was used for the development of the paints, which led to increasingly complicated formulas. Among the components used were for example biocides, ethyl alcohol, turpentine, asphaltic bitumen, zinc oxide, zinc dust, and red oxide(Candelas, 2018). Later, the anti-fouling properties of Tributyltin (TBT) were discovered. It was first used as a biocide in a self-cleaning copolymer patented in 1976, and thanks to its high effectiveness, it became widely used, but it is toxic at extremely low levels (Jackson, 2008) .

The high toxicity in products with TBT began to cause significant problems in a wide range of species in the marine environment. The harmful effects of TBT on species such as mollusks led to its use being banned in different countries during the 1980s, which suspended its use in vessels of less than 25 meters in length. Later IMO developed the Anti-fouling Convention, and the global ban on the application of TBT-containing paints from 2003 was established.

In Figure 19, the most relevant milestones in the development of anti-fouling paints are presented in a general timeline.

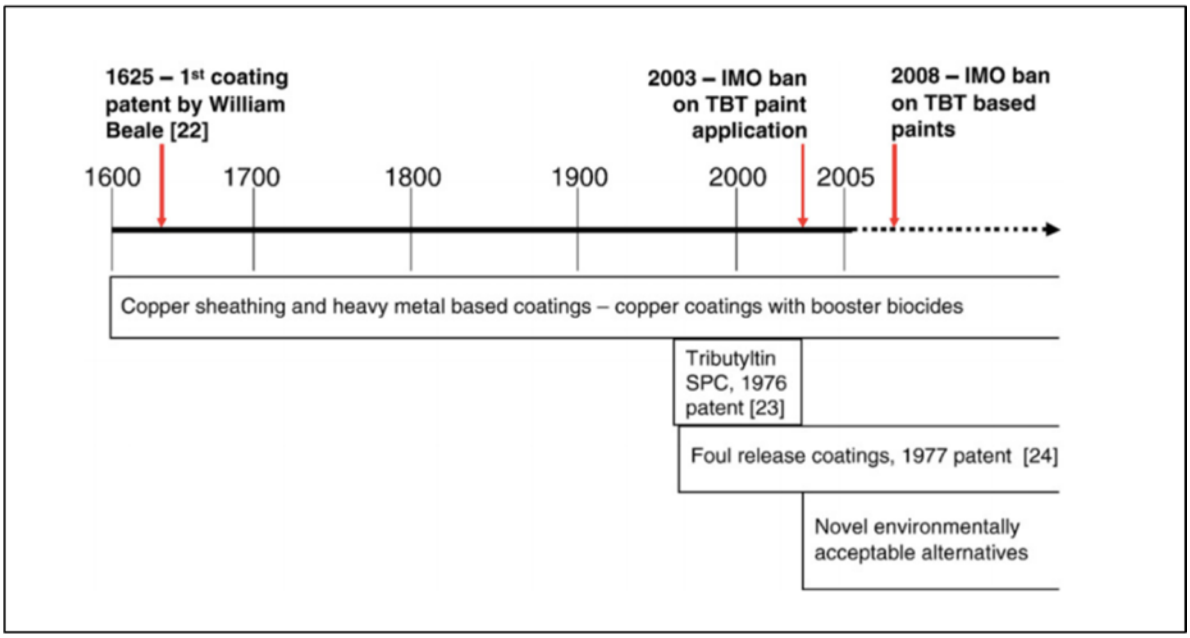

Figure 19 most relevant milestones: The evolution of antifouling paintings in history;

Source: "Modern approaches to marine antifouling coatings" by L.D. Chambers, K.R. Stokes, F.C. Walsh, R.J.K. Wood. June 23, 2006

4.2.1 Antifouling systems: From biocide content to non-biocide coatings

There is currently a variety of antifouling coatings on the market. In this work, antifouling coatings will be grouped into two main categories according to the mode of operation and whether they depend on the release of biocides to prevent biofouling.

• Biocidal coatings, which are used by almost 90% of the maritime industry, are characterized by releasing chemicals such as copper compounds, to prevent settlement or survival of aquatic organisms (Anderson, 2016).

• Biocide-free coatings do not depend on chemicals or pesticides but depend on their physical nature (Callow & Callow, 2011). Modifications to the surface to create a softer surface ensure that the encrusting species cannot adhere and are easily removed when a ship is sailing.

It is essential to consider several factors when choosing what type of antifouling coating will be used. The following factors should be considered:

- What is the profile of the activity that the boat will carry out; this is because the antifouling systems are developed to work, for example, at specific speeds or environments.
- Another point to consider is the time that the ship will be operating without making a replacement in its coating system. Each antifouling paint has a specific useful life which is affected by external factors such as salinity and temperature.
-The coating must be compatible with the construction materials and with the places most affected by fouling, such as the niche areas; therefore the design and construction of the ship play an essential role in choosing which antifouling technology will be used (Jackson, 2008).

Due to the prohibition of the use of TBT as of January 1, 2003, and its presence on ships after January 2008, paint manufacturers have developed antifouling biocidal paints that are more compatible with the environment.

The new biocides paints can be grouped into three main groups depending on the soluble acid binder that allows the release of biocides in seawater:
- Controlled Depletion Polymer (CDP)
- Self Polishing Copolymer (SPC)
- Hybrid systems.

Non-TBT Biocidal Antifouling release process

These types of paints are characterized by the release of biocides or toxics at a specific rate that is called "leaching rate" or "release rate." Biocides are released in a film or layer on the painted surface, controlling the fixation of animal and plant species mainly in their larval and spore stages. For the manufacture of this type of antifouling paints, biocides or repellents of mineral origin can be used, such as copper; organic biocides with low environmental impact, and natural from vegetables (Caprari, 2006).

Each biocide is effective in certain types of encrustations, for example copper-based biocides are generally very effective against the encrustation of animals, but their effectiveness against plants and algae is very limited. On the other hand, Co-biocides or Boosters are more effective with algae and slime but very little recommended to avoid animal fouling, as can be seen in Figure 20.

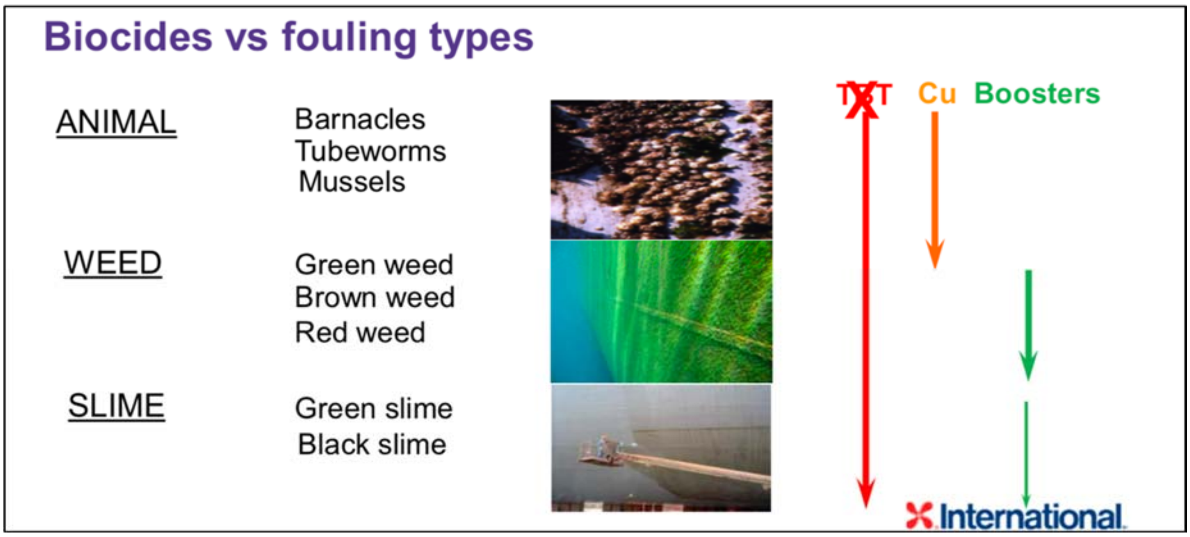

Figure 20 Types of biocides vs fouling types.

Source: Colin Anderson Presentation

Biocide release mechanism in coating

The performance of the Biocidal antifouling coating depends to some extent on the speed with which specific biocides dissolve in the sea, on the adjacent surface of the ship. This can be affected by water temperature, salinity, and the flow rate of water on surfaces.

The layer created by the paint acts as a biocide reservoir, which gradually decreases until it is completely removed. In this way, the ship will only be free of fouling while the biocide is concentrated in the surface water layer.

The speed at which the biocide dissolves is a crucial factor for this type of paints because if its release speed is too fast, the paint will end soon and its effect will be in vain; however, if its release rate is very slow the antifouling will be ineffective especially in areas with high fouling concentration (Nicholson, 2012).

In summary, the chemical process for the release of biocides can be explained as follows: The biocide antifoulant has an acidic binder component that can dissolve, which reacts with the alkalinity of seawater (pH ~ 8), thus releasing the contained biocides (Barnes, 2018).

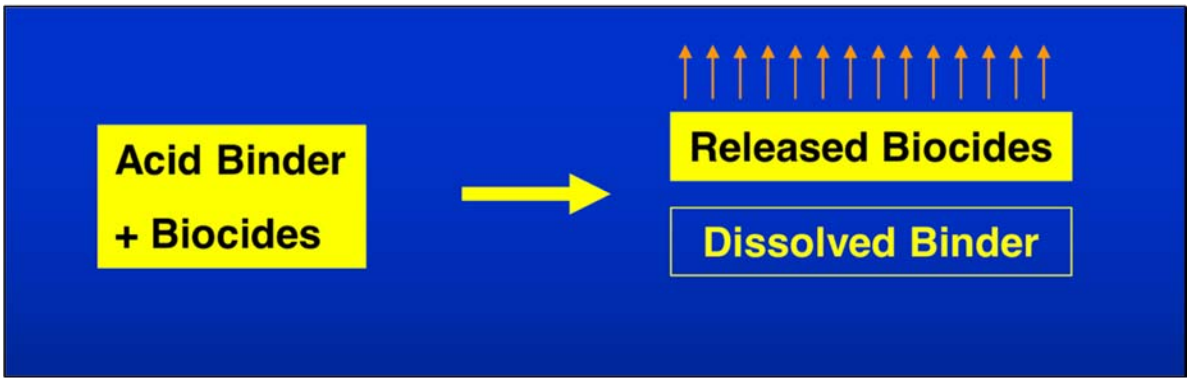

Figure 21 Chemical Process for the release of biocides.

Source: Colin Anderson Presentation.

Controlled Depletion Polymer (CDP)

These antifouling paints are a development of traditional soluble matrix paints. They are also known as abrasibles / erodibles, and they contain a large proportion of a water-soluble, physically drying and non-toxic binder. This binder is reinforced with polymeric ingredients capable of controlling the relative speed of dilution / erosion through physical processes. The level of biocide released can be regulated. In contact with seawater the biocide is released together with the soluble binder, which is washed from the surface.

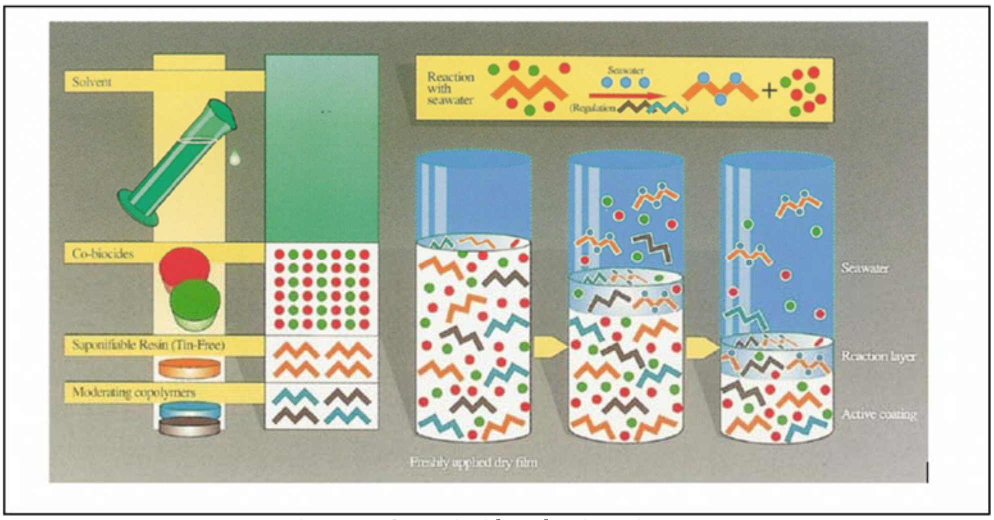

Figure 22 CDP Biocide Releasing Diagram.

Source: E. Almeida et al./ Progress in Organic Coatings

These type of paints are based on the use mainly of rosin, which is extracted from trees and is used because it is slightly soluble in seawater. However, Rosin has some disadvantages that make this type of paint not the best option in terms of efficiency (Anderson, 2016).

- It is a brittle material and can cause cracks and detachment in the paint.
- Reacts with oxygen and must submerge relatively quickly.
- Does not prevent water from penetrating the depth of the antifouling paint film.

Figure 23 illustrate how the biocide release process is carried out. First there is a slow dissolution of the paint film in seawater; subsequently, the solution gradually slows down over time, due to the formation of insoluble materials on the surface, which creates a layer. The leached layers can become thick over time, preventing the release of biocides and increasing roughness.

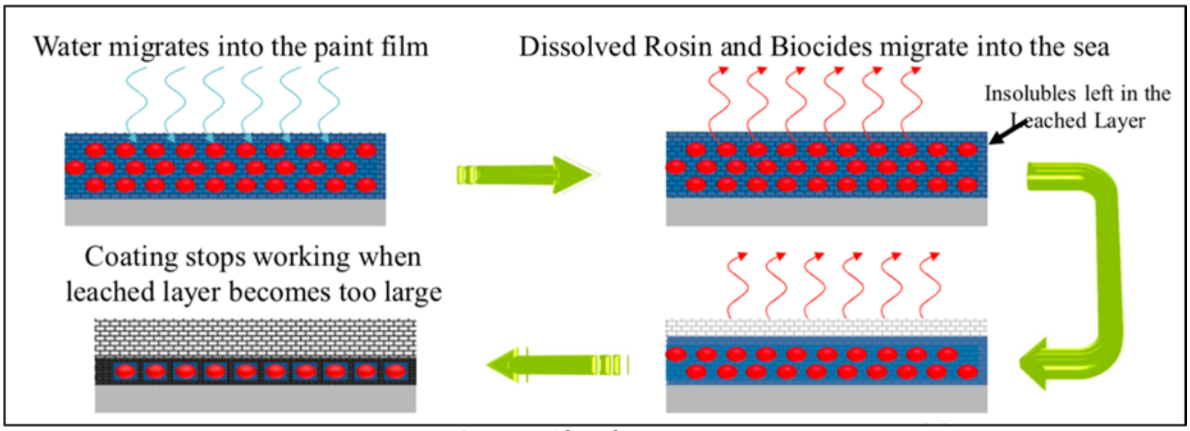

Figure 23 CDP Biocide Release Process.

Source: Colin Anderson Presentation.

CDP antifouling paints are not as effective as the SPC systems that will be explained below; however, they are the lowest cost antifouling paints per square meter and their useful life can reach 3 years.

Self-Polishing Copolymer (SPC)

These types of antifouling paints are hydrophobic before immersing them in salt water. Once in contact with salt water, they undergo a chemical reaction called "hydrolysis", where sodium chloride breaks the bond between the polymer and copper, creating an acidic acrylic polymer. This makes them hydrophilic. The acid polymer is only created on the surface, not in the entire layer thickness. The reaction on the surface occurs constantly, recreating in it the acidic polymer; the biocide is released in a controlled manner and the acidic polymer dissolves in the water (Nicholson, 2012).

These formulations have copper acrylates, which, when reacting with the sodium ion present, produces the polymer hydrolysis and dissolution of copper. Zinc-based copolymers are also used as binder agents, and zinc acrylates or carboxylates, whose mode of action in seawater is produced by ion exchange. Finally, methacrylates functionalized with silanes can also be used. In these, the tin atom is replaced by silicone, giving a compound similar to those that TBT products had before their ban.

In this type of products, the radical can be alkyl, aryl, propyl, or butyl, according to the properties that are desired. To regulate the solution and obtain the proper hydrolysis rate in these systems, the polymer must be plasticized internally or externally (Caprari, 2006).

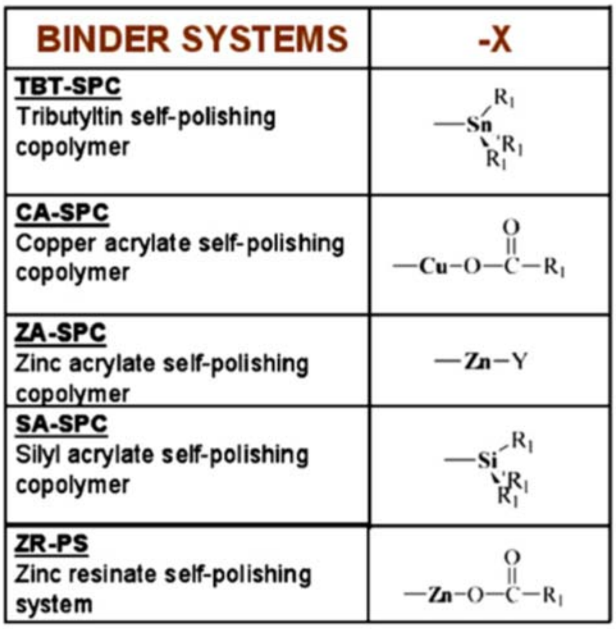

Figure 24 Binder Systems used in SPC paints.

Source: E. Almeida et al./ Progress in Organic Coatings

These types of paints are mechanically stronger than CDP paints. By using a more controlled chemical dissolution system of the paint film, it grants a more prolonged duration between periods of dry dock, which can reach 90 months. As the layer becomes thinner, the surfaces become smoother. Other advantages of SPC paints is that they are ideal for application on new ships because their properties give it excellent weather resistance and good fouling control even during the conditioning stage. In addition, SPC paints are suitable for use in freshwater (Barnes, 2018). For these reasons, SPC products are considered to be high-end, and their price is higher than CDP, which represents a disadvantage.

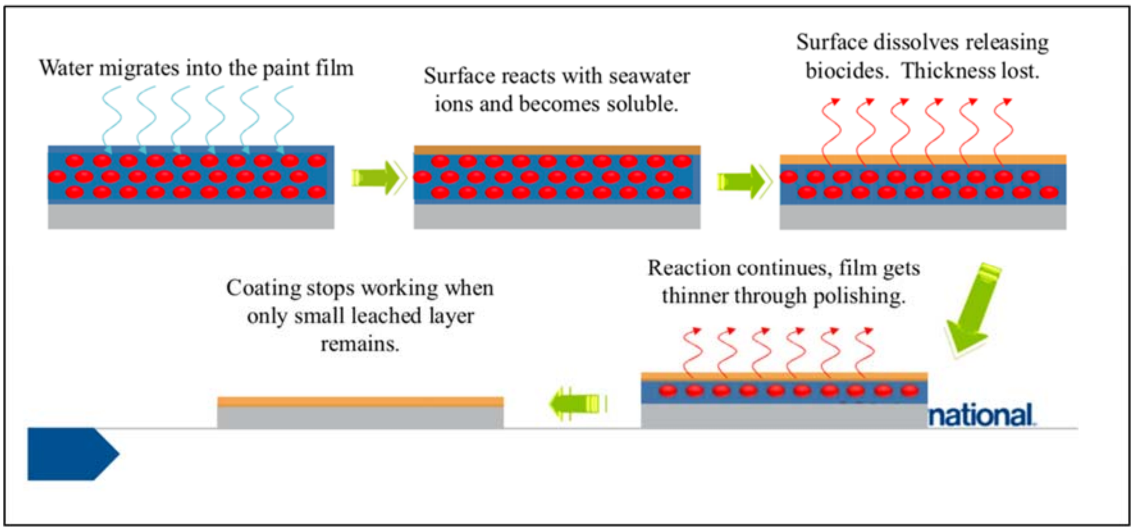

Figure 25 SPC Biocide Release Process.

Source: Colin Anderson Presentation

Hybrid systems

SPC hybrid technology was designed to provide intermediate performance at an intermediate cost between CDP and SPC products as can be seen in Figure 26. However, detailed information is not provided by paint manufacturers.

Hybrid products work through a mixture of hydrolysis and hydration mechanisms, combining SPC acrylic polymers with an amount of rosin. The most used biocide as a booster in this type of technology is copper pyrithione, which is more effective than any of the boosters used in CDP products (Anderson, 2016). Among its main features are:

- Self-polishing and self-smoothing
- Limited leached layer
- Up to 60 months of service life.

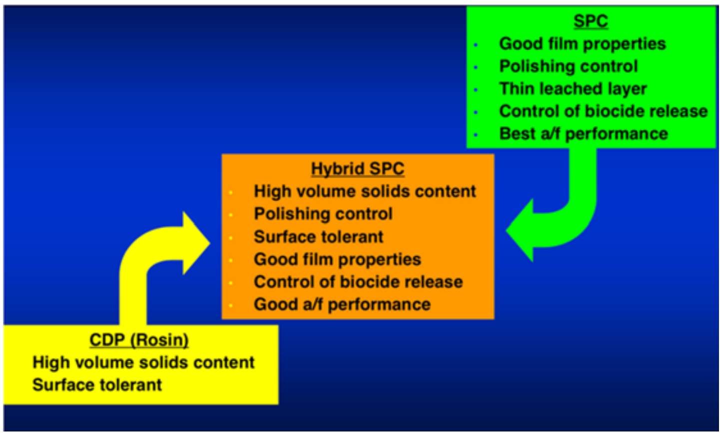

Figure 26 Comparison between different types of antifouling paints.

Source: Colin Anderson Presentation.

Non-Biocidal Antifoulings

The main objective of antifouling paints is to avoid fouling on ship hulls. However, this function usually involves the use of biocides that despite their good results, are still toxic substances sent to the marine environment, and that can negatively affect the species that inhabit there.

In the current biocidal prohibition environment for antifouling paints, innocuous products have been developed to avoid environmental risk. These products act differently from traditional paints. “Foul release coatings” work through a physical means, and they do so essentially through a barrier layer that also has an ultra-soft surface that ensures low friction and is also hydrophobic, so marine organisms cannot adhere to the same. If the fouling adheres to the hull, due to the soft surface created, the adhesion will be weak and if it is in an initial phase, it is very easy to scratch and does not require much effort to remove. These types of paints are very useful in vessels where divers regularly clean the hull.

One aspect to consider is that foul release coatings do not contain biocides and therefore cannot constantly repel the appearance of fouling in the hull (Nicholson, 2012). Another point is that these paints are not strong enough in extreme conditions, such as ice, and under these conditions the coating is damaged, the roughness increases and the non-stick properties are lost. It is considered that for these coatings to be effective, they should be used on ships operating at more than 18 knots (Gabaldón, n.d).

Silicone-based coatings and fluoropolymers are the polymers with the best performance when obtaining low adhesion and also have decent mechanical properties (Townsin & Anderson, 2009).

According to Anderson (2018), among the main properties or characteristics of biocidal free products or "Foul Release" are:
- The smoothness of its surface: These coatings provide an ultra-soft and slippery surface, which makes the fouling adhesion to the ship's hull very difficult.
- Lower weight: Compared to other types of anti-fouling technologies, coatings without biocides are lighter because they have a lower specific gravity. For example, paints with biocides have a specific gravity, between 1.5 - 2.0, which is higher than the average of most foul release systems whose specific gravity is close to 1. To the fact that the FR coatings have lower specific gravity is added that FR systems use fewer layers of paint and solvent when applied to the hull of ships.
- Lower operating and maintenance costs: Maintenance costs are reduced because it is not necessary to enter a dry dock so often. In some cases, in a period of up to 60 months, it is only required to touch up the hull cleaning, and after these 60 months, a reconditioning of the coating can be carried out, which represents a shorter stay in the dry dock and more flexible maintenance intervals.
- Easy cleaning of the hull: Due to the smoothness granted by this type of coatings, which prevents a strong adhesion of the fouling to the hull, the cleaning is simpler since no major specific treatment is needed to remove the fouling from the ship.
- The roughness of the hull: FR coatings have an average roughness of the hull below 100 microns, which makes them softer than most antifouling paints with biocides. The smoothness of the surface of the hull helps the energy efficiency and saves fuel and lower gas emissions. In addition to these properties, being a technology based on silicone chemistry makes them quite durable both in and out of the water.
- Without Biocides: Perhaps the most important point in favor of this type of coatings is the fact that they do not use biocides, which is the objective of both IMO and the

different countries that increasingly have more regulations to control the use of biocides. The point against the use of this type of technology is that in order for them to be effective they must be applied on ships operating at more than 18 knots.

4.3 Development of new antifouling technologies

As alternatives to the use of biocidal paints and foul release technologies, other techniques such as ultrasound waves, electric currents or cathodic protection and use of natural products to avoid fouling adhesion to helmets, among others, have been proposed.
This development of new techniques has been effective for certain types of bivalves, since, as mentioned in Chapter 2 of this work, there is a lot of variations in the nature of the fouling, which also establishes variations in the degrees of tolerance that each species has. However, despite the numerous alternatives, the difficulty and cost of applying them to ship hulls have limited their extension and testing to other different species found in other marine environments (Almeida et al., 2007).

4.3.1 Nature-based antifouling systems, mimetics and other alternatives

Antifouling agents have been identified in certain bacteria, algae, corals, sponges, and land plants. For this reason, studies are currently underway to use these products with polymer matrices of antifouling paints, which prevent the adhesion of marine organisms, without releasing components and without contaminating the environment.

Another field of research is the study of the surface of certain marine animals such as dolphins and whales, which remain throughout their lives without suffering significant fouling on their skin, which indicates that the skin has non-stick properties. This seems to be due to the presence of low surface tension glycoproteins on it. From a hydrodynamic point of view, the three interest groups of marine animals in this field are cetaceans (whales and dolphins), teleost (bony fishes) and Slamobranchs (cartilaginous skeleton sharks, rays, etc.). Although the study is still at an early stage, the observations suggest the use of micro structured silicones, to prevent the grip of marine organisms (Almeida et al., 2007).

Electrical and electromagnetic systems.

In these antifouling systems, a potential difference is created between the hull of the ship and the sea that causes a chemical process that prevents the formation of fouling. This technology is very effective but extremely expensive and could facilitate corrosion.

Marine Growth Prevention System (MGPS)

This system is based on impressed current and is ideal to prevent marine organisms from depositing completely inside the ship. The operation consists in the use of current, through the use of sacrificial anodes and steel cathodes that are connected to an electric rectifier with a controller. The system generates copper ions mainly by electrolysis in salt water. These ions flow into the system thus creating an environment that repels the adhesion of microorganisms. The sacrificial anodes used are usually made of iron or aluminum, which are usually replaced every time the vessel is in a dry dock (Cathodic Marine Engineering, 2019).

The main advantages of the system by printed currents are:

- Dual protection against corrosion and fouling
- Easy installation
- Easy maintenance
- They cover different types of ships and different lengths

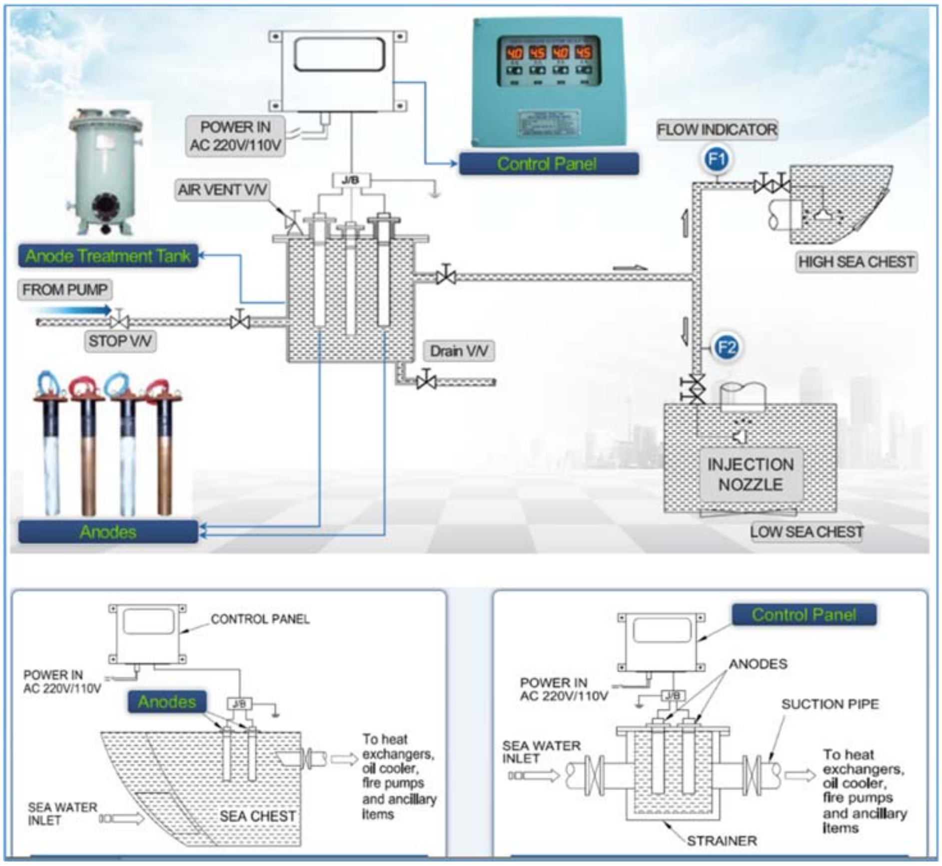

Figure 27 MGPS System operation scheme

Retrieved from http://www.shanghaichuhai.com/html_products/Marine-Growth-Prevention-System-52.html

Ultrasound emitting systems.

Ultrasonic emissions are emitted along the hull that disturbs adhesion, however, and despite their effectiveness, these could create another problem for the marine environment such as underwater noise.

4.4 Comparative analysis of antifouling technologies in use by New Zealand Government

The best way to prevent the introduction of IAS is prevention through good hull maintenance practices and through the installation, operation, and maintenance of appropriate antifouling systems.

The New Zealand Government decided to get involved in a project that gathered information from various fields of the maritime industry such as operators, marine coating companies, class societies, and information from dry docks.

The objective of this project was to identify effective maintenance practices for hulls and niche areas and at the same time verify which is the most effective AFS applied to different types of vessels studied.

For this project, which was supported by IMO, information was collected from 50 different ships, which had different characteristics such as: Operation area, type of vessel, Dock interval, ship speed and most important type of antifouling used.
In order to carry out the study, information was obtained on ships painted with the three types of coating used in the maritime industry: CDP (soft and hard formulations), SPC, and FRC.

The Results

Hulls

After analyzing the data obtained from the various types of vessels studied, it is possible to determine that in the case of Boot tops, all antifouling systems were affected in some way by the growth of macroalgal, regardless of whether or not a system with biocides was used. The difference in the amount of macroalgal attached is given by the docking cycle, the shorter the docking cycle, the more percentage of the vessel is covered by algae, especially in periods under 36 months.

Vertical Sides of the Hull

In this case, the soft fouling increases in its percentage of extension as the in-service period increases, in these cases the vessels equipped with SPC coatings are the ones that prove to be more effective in preventing the adhesion of soft fouling.

Hard fouling

CDP coatings were the most affected, reaching almost 60% coverage. Hard fouling adhesion began at an early stage close to the first 8 months. The latter contrasts with the effectiveness demonstrated by the SPC and FRC coatings that remained without adhesion of hard fouling until 60 months.

This efficiency demonstrated by the SPC and FRC systems was only affected when they were applied on ships operating at slow speeds. In the case of CDP paints, there is no direct relationship between ship speed and antifouling efficiency. On the contrary, for the SPC and FRC systems, the operating speed is important because there is a decrease in the amount of fouling attached to the hull when speeds greater than 12 knots are used.

Intake grates and rudder

The amount of fouling attached to the intake grates varied between vessels types. According to this study, the foul-release coatings have better performance compared to other kinds of biocidal coatings. The same results were obtained for the rudder, where FR systems proved to be more effective and durable.

Conclusion

This study concludes that to achieve better prevention and minimization of biofouling, is preferable to use SPC and FRC coatings, regardless of the period in service. However, it is necessary to take into account that an important factor when choosing the type of coating is the speed and activity of the Ship. If CDP or SPC is to be used, it should generally be applied to slower, less active vessels, especially CDP. SPC coatings are suitable for all types of ships, although they present the problem of being more expensive. FRC coatings are very effective but only for vessels that operate at medium to high speed, over 18 knots, and with high activity. CDP coatings were less effective in combating biofouling growth compared to the other two types of coatings; this also explains their lower cost in the market.

Another conclusion that can be obtained from this study is with respect to interior areas such as intake grates, and sea chest. For intake grates, the best system that can be applied is FRC, which can help maintain optimal functioning and reduce the level of biofouling accumulation. For the chest, the results showed that soft coatings work better than hard coatings to prevent biofouling growth.

In the next chapter, another problem related to biofouling and its removal from ship hulls will be described, and how In-water Hull cleaning and AFS shore based removal can represent another focus of introducing IAS into new marine ecosystems.

5. Chapter V: In-water Hull cleaning and AFS Shore Based Removal

In this chapter the operation of In-Water Cleaning is discussed to identify its role related to the IAS spreading to the aquatic systems. Moreover, this chapter presents the associated risks with the In-Water Cleaning, such as chemical contaminations risks and biosecurity risks. Further, the different methods and technologies are introduced, which are currently used with their advantages and disadvantages. Furthermore, the chapter highlights the importance of shore based facilities and their role in collecting the disposals and ship waste that contribute to minimizing the impact of transferring the IAS to aquatic systems.

The accumulation of marine organisms on vessel hulls affect their performance, in addition to increase the impact of spreading the invasive aquatic species. Therefore, the ship hull needs to be cleaned regularly to improve the ship performance and reduce the impact of transferring marine species. However, the application of the cleaning and antifouling removal could contaminate the aquatic system due to the release of fouling paint during the operations. To carry out such operations safely, measures have been introduced e.g. Australian Anti-Fouling Act and in Water Cleaning Guidelines. The guidelines provide different ways to minimize the impact of the In-Water Cleaning, which will be presented in the following.

The In-Water Cleaning process is an essential tool to reduce the accumulation of fouling on the ship’s hull. Thus, there are two major benefits which are reducing the transfer of non-indigenous species and supporting IMO efforts on EE as well as comply with related IMO instruments (IMO, 2011c).

However, this particular job, In-Water Cleaning, may have detrimental impacts on local ecosystems because it releases species which were attached on the hull.

Therefore, in-water cleaning is banned in many jurisdictions due to the fact that it poses risks to the marine environment. Basically, these risks are of two categories:

1. The release of the hull chemical contaminants which come out from the ship coating.
2. The release of non-indigenous species to new areas which could damage the marine ecological system

5.1 Chemical contaminants released during in-water cleaning process

Copper is the most active component in antifouling painting systems, yet, it is assumed a high toxic to the marine environment. Therefore, releasing even a small portion of it during the In-Water cleaning procedures would contaminate and endanger the ecosystem diversity (Morrisey, 2013). Moreover, the concerns of releasing contaminate chemicals like copper during cleaning process are related to the use of biocides AFS paints (Australian Department of Environment, 2015). Further, these biocides painting are mainly divided into three categories:

- Soluble matrix
- Insoluble matrix,
- Self-polishing copolymer

5.2 Biosecurity Risk related to In-Water cleaning

The in-Water cleaning could cause also biosecurity risks to the marine environment where this process is undertaken. Hence, such operation could release the non-indigenous species unless there are effective collecting/capturing mechanisms whilst the process is carried out to minimize the unwanted consequences (Morrisey, 2013). Current methods that can cause potential release of fouling:

- Soft-cloth removal mechanism of slim layer can be highly probable of releasing a significant magnitude of microbial organisms to the marine environment;
- Hand-removal of spot fouling could also lead to a significant release of soft/ hard fouling;

- Brush-based removal for both slim layer/hard fouling could have a high likelihood of releasing slim and motile fouling to the marine environment without effective capturing of the released particles (Morrisey, 2013).

Further, the biosecurity risks accompanying in-water cleaning could be mitigated by capturing the wastes produced during the operation, yet the current technologies are limited to make certain that most of the released wastes are captured. It should be kept in mind that, the soft-cloth operation was carried out with special divers running through the entire ship's hull; in other words, the chances are small to capture all the released waste within restricted time and capability of tools (Morrisey, 2013).

5.3 In-Water Cleaning Technologies

However, the diver assisted cleaning system could be more effective especially in some complex areas in the ship hull, compare to the automated brush cleaning system, which would clean less areas besides having less abilities in terms of capturing the released fouling (Davidson, McCann, Sytsma, & Ruiz, 2008).

There are a vast number of cleaning technologies available, the most commonly of which are brushing/scrubbing and also the usage of soft cleaning systems e.g. soft-cloth, in addition to air-water jet systems. These different technologies are varied according to their effectiveness and their assigned jobs depending on the AFS and coating types (Australian Department of Environment, 2015).

- **Brush System :** This method is widely used for its ability of cleaning the surface without damaging the biofouling coating and causing biological releases to the environment. It can be used in a wide range of coating types, besides, it could refresh the coating efficiency. However, the existing brushers are not fully sufficient to remove all the biofouling on the surface including (niche areas), for the reason that brushing systems can affect fouling-release coating surfaces; therefore, it is not recommended that such type of coating be used unless the brushes are sufficiently soft and do not to damage the coating.

- **Soft Tools :** This method is effectively used with fouling release-coating where it cause no harm to the surface of the coating e.g.(squeegees, wiping tools, and cloth). Moreover, these tools are powerful in removing microfouling and macrofouling effectively in addition to securing the coating from scratching or damaging its characteristics.
- **Water jet and air jet (blast) systems :** The water jet tool has multi uses according to the pressure applied, coating type, jet pattern, and angle. However, the effect of the water jet is still uncertain as it could be varied depending on the coating systems In addition, the water jet method is not able to cover all types of fouling or different coating systems.

5.4 Decision Support Tool In-Water Cleaning (Australia)

The decision required to carry out the operation of in-water cleaning can be complicated because it requires thorough assessment to reach out to the optimum decision. Therefore, the following decision support tool, which was introduced by Australia, is important to all relevant authorities to carry out such steps or adopt similar tools to achieve the goal of protecting the environment of the impact of biofouling. Again, this tool could be helpful for ship operators to identify the required information and documentation that might be asked by the relevant authority (Australian Department of Environment, 2015).

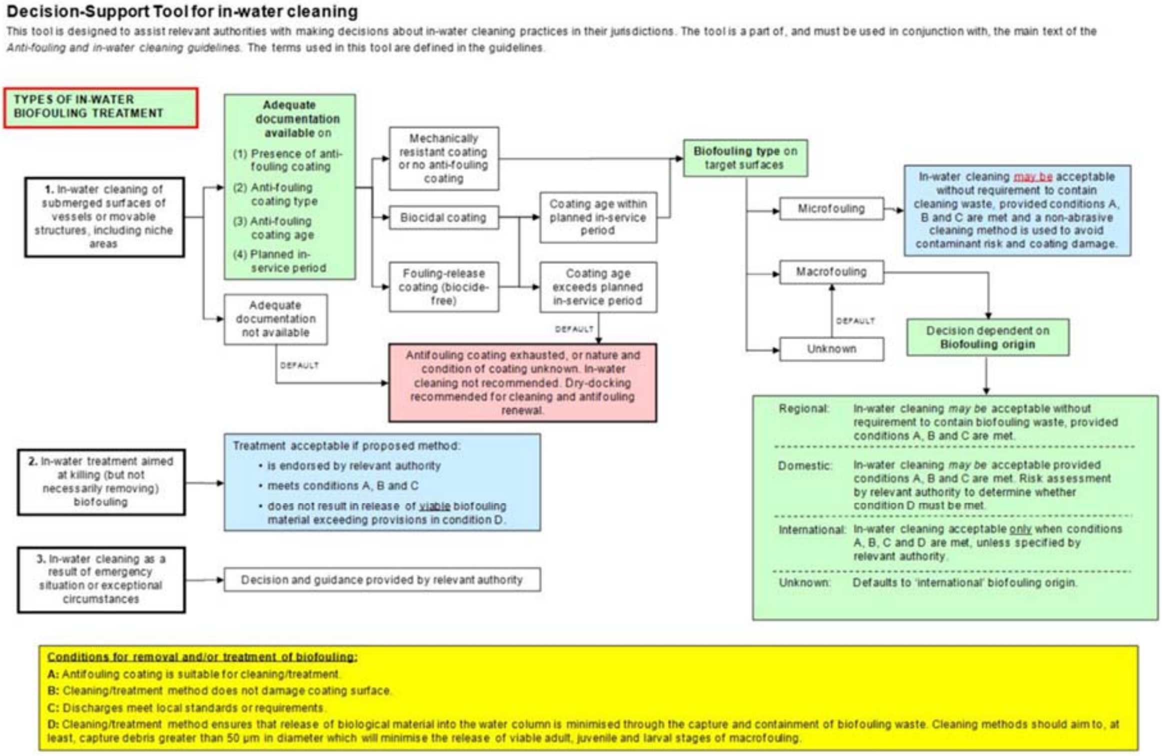

Figure 28 Decision – Support Tool.

Source: Australian Anti-fouling and in-water cleaning guidelines.

Figure 28 shows the main three categories for the decision making process, which are the type of the systems whether 1- in-water cleaning for submerged surface 2- in-water cleaning aiming to kill but not necessary to remove the biofouling 3- in-water cleaning for emergency situations; the paint and their related condition information; the type of targeted fouling on the ship hull. However, in case of lack of the required documentation or available information from the related authority, the following points should be considered as simple guidance to make a decision:

- The type of the coating whether it contains biocides or is biocides free, in case of uncertainty it should be assumed with biocides.
- The age of the painting should be assumed if the age can not be determined.
- Whenever the type of biofouling painting is unknown, then it should be considered as macrofouling.
- If the origin of the biofouling is unknown then it should be assumed as an international origin.

Finally, this decision support tool it is just a basic mechanism that might be helpful to the interested party; however, it could be improved or developed by any relevant authority seeking to implement the most effective measures to mitigate the impact of biofouling to the environment.

5.5 Shore-based removal of anti-fouling coatings

The shore based removal of anti-fouling systems should be carried out in applicable facilities that ensure proper containment of the waste and disposal which could be harmful to the marine environment. Hence, for example, Australia adopted local measures that ensure the proper waste control and all disposal should be treated in order not to release theses contaminates to the local ecosystem (Australian Department of Environment, 2015). Subsequently, Australia has local guidelines as solutions to combat the impact of released fouling especially regarding the shore based AFS removal, which address certain requirements for the shore based maintenance facilities.

5.5.1 Requirements for the shore based maintenance facilities (Australia)

- The operators should be familiar with the best practices recommendations indicated in the guidelines regarding the maintenance and removal of AFS , and to be informed to all customers.
- Operators should adopt measures confirming the capturing of all waste and disposal of AFS during the processes in the facility and treat them to minimize their impact to the aquatic environment.
- The facility has to have designated areas where maintenance activities and their productions of waste are isolated from the environment.
- The facility should have clear rules that the operators must adhere to accordingly.
- The facility has to collect the coating and biofouling waste and dispose them in accordance with the followed local regulations.

5.5.2 Anti fouling Removal Methods in Yards

There are several methods available in terms of AFS removal, each of which require special considerations due to different factors (Australian Department of Environment, 2015).

- **Hydroblasting** : also called water jetting uses a very high water propelled pressure or ultrahigh pressure to remove the coating out of the hull surfaces. In this type abrasives are not used. There are factors to be considered in this method :

1. During the process the spray causes the coating to drift in the air; therefore, the wind condition should be considered besides the use of screening.
2. The antifouling systems are highly toxic, and for that reason, the area where such operations are carried out should be isolated from the environment. In addition, the workers have to be properly protected from such hazardous substances.

- **Abrasive Blasting** : also known as grit blasting, uses air pressure, water pressure or centrifugal force in order to remove the contamination of the coating and rust as well as old painting. The commonly used abrasive blasting is sand, iron shot, steel grit, iron grit, and copper, besides aluminum oxide. Further, there are dry abrasive blasting normally using sand blasting and wet abrasive which is helping to suppress the dust generation. Furthermore, there is vacuum blasting which includes a vacuum property that works to capture the residue during the process keeping the vicinity safer. Moreover, there are important factors to be considered while carrying out this method:

1. Anodes, physical fittings should be removed prior to abrasive blasting especially dry blasting to avoid damaging them.
2. In the situation where vacuum abrasive blasting is not available, the following options should be considered :
    - An abrasive blasting chamber with effective dust collecting and ventilation.
    - Ensure the existence of screening to outdoor or open in addition to suitable material of isolation e.g. UV to minimize the impact of drifted dust .

3. Dry abrasive blasting should be executed in enclosed areas to contain the dust.

<u>5.5.3 Disposal of Residual material in dedicated facilities</u>

The operation of removing the AFS from ships create a great many contaminant residuals which could impact the aquatic and terrestrial environment. Therefore, the engaged states have considered facilities able to accommodate such material. Australia for example considers the following :

- Any removed material from the ship or created during the operation of paint removal should not be allowed to be disposed into the water and not even be allowed to be in contact with any water sources, besides, it should not be in touch with land below the water level.
- All types of waste liquid, solid coating, biological and chemical should be collected and stored in an appropriate way where they should later be disposed of according to the requirements of the relevant authority.
- The wasted coating should not be incinerated as they would generate toxic gasses and fumes that impact the environment.

In the same context, to address the importance of the reception facilities the Ballast Water Management Convention on Art.5 has stressed on the necessity of the availability of reception facilities for the ship waste and sediments where ballast tanks are cleaned or repaired. Thus, to minimize the impact of spreading marine organisms to the aquatic system nearby. Moreover, the Guidelines for Ballast Water Reception Facilities (G5) have mentioned the importance of implementing reception facilities, keeping in mind that, it is not referring to the Art.5 yet, but it is broadly encouraging the ports and ships to uniform their efforts to implement the reception facilities in order to minimize the impact of the transfer of invasive aquatic species.

In other words, the In-water cleaning process is the second step to deal with the issue of biofouling accumulation. Where the first step is the use of Antifouling systems; however, as mentioned earlier ship's hulls need to be maintained and cleaned regularly to preserve hulls' smoothness and AFS effectiveness. Although, these operations could lead to the spread of the invasive aquatic species to the local areas by releasing attached marine organisms causing environmental disorders. Therefore, conducting in-water cleaning operations should be carried out according to specific measures emphasizing on minimizing the spreading of IAS. For example, Australia has introduced special guidelines for in-water cleaning operations stressing on the importance of containing the waste and disposal of ship’s hulls cleaning, besides, the removal of the antifouling paint. Also mentioning the significance of shore-based facilities and mechanisms of controlling and collecting the disposal to reduce the risks of biofouling release and antifouling wastes.

6. Chapter VI: Conclusions and Recommendations

Since ancient times, the problem of adhesion of marine organisms on submerged surfaces in seawater, particularly on ships hull, has been a concerned. In the past, the loss of speed or efficiency experienced by ships resulting from hull fouling was the main focus.

Many solutions were developed to combat fouling, the most commonly solution was to use copper sheets. The use of copper extended for long periods. The development of steel ships required new solutions. For such vessels, antifouling coatings containing biocides were developed. These paints remove the organisms without producing galvanic corrosion.

In addition to reduce ship efficiency and speed, hull fouling also carries organisms between various biogeographic regions. Today it is proven that biofouling represents a severe risk to the environment and the economy. Some non-native species transported by biofouling can modify and harm recipient environment as well as become invasive.

In short, the main impacts produced by biofouling can be divided into three main aspects:

- The risks of introducing invasive aquatic species, which travel adhered to the biofouling of ships. The effect produced by these IAS ranges from the reduction of fisheries production to the economic damage caused by the closure of tourist centers due to the presence of algae, including the damage to local biodiversity and the cost to public health that can produce the pathogens introduced by toxic species.
- The problems caused by the increase in the roughness of the hull, due to biofouling, increase underwater resistance which affects ship efficiency. Consequently, more energy is required for the same amount of work (speed)

which increases fuel consumption, and GHG emission as well as operating costs.

- The last problem is related to the toxicity of biocide-based paints, especially those with TBT that were created during the 60s and 70s. Despite high efficiency in avoiding biofouling, TBT paints have harmful effects on non-targeted marine species, causing death or genetic alteration.

The International community represented by IMO has responded to the issue of biofouling and TBT-based antifouling by adopting regulations and guidelines.

- The IMO has introduced the AFS Convention to regulate the components used to create antifouling paints. The most important points of AFS Convention is the ban of organotin compounds which act as biocides in antifouling systems as of January 1, 2003, and the prohibition of future antifouling systems that represent a threat of serious or irreversible damage to the marine aquatic environment and/or human health.
- Furthermore, to tackle the problem of the invasive species transferred by ship's hulls IMO has published the Biofouling Guidelines. The Guidelines aims to minimize the impact of transferring of IAS via ships' hulls by providing recommendatory practical measures. Despite IMO Biofouling Guidelines, some other countries have established their own national regulations. For example, United States (California), New Zealand, and Australia have established stringent national regulations to combat the issue and to protect their marine environment, as the international Biofouling Guidelines were not sufficient enough to confront the issue.
- The IMO has also considered the biofouling from energy efficiency perspective. When adopting the MARPOL Annex VI chapter 4 on Energy Efficiency Regulation, the IMO developed guidelines on SEEMP promoting, inter alia, hull cleaning.

After IMO ban on TBT, shipping industry and paint manufacturers turned to try to find effective solutions without harming effects to the environment. This search for an effective and environmentally friendly solution has led to the creation of a wide variety of antifouling coatings available in the market: biocidal and non-biocidal paints.

However, when choosing what type of antifouling to be applied to a ship, it is necessary to consider various factors such as the operation profile of the vessel, the area where it will operate, the speed of the ship and dry docks periods (among other things).
The most used antifouling systems are biocide-based. They cover about 90% of ships worldwide, however, the current trend promotes coatings without biocides.
Antifouling coatings that contain biocides are divided into three main groups, depending on how they release the biocides: Controlled Depletion Polymer (CDP), Self Polishing Copolymer (SPC) and mixed systems.
Systems that do not use biocides, also called Foul release coatings, act by physical action. The coating creates a smooth (slippery) surfaces to which organisms cannot easily adhere. Therefore, organisms are removed by the action of water during navigating or by pressurized water. These systems have a good reputation due to their environmentally friendly mechanism of action. They also lower operating costs: fewer dry dock entries to clean the hull; smoother surfaces reducing drag (less fuel consumption); easy cleaning of the hull. However, the main drawback of foul release coating is that ships must operate at a medium to high speed to detach fouling - usually exceeding 18 knots.
In addition to the technologies described above, numerous alternative techniques to antifouling have been developed but they prove ineffective, too expensive or difficult to apply in ship hulls. That is why technologies such as the use of alternative currents, ultrasound, or mimetics (e.g. shark skin) are under development.

To restore smoothness of antifouling and remove biofouling, it is necessary to perform regular cleaning in dry-dock or in-water. The In-water Cleaning operations remains cheaper and do not disturb ship operation and can improve the ships' performance and avoid transport of unwanted species. Further, IMO Guidelines recall the importance of in-water Cleaning: enhancement of ships' energy efficiency and avoid movement of aquatic organisms.
In-water cleaning could be carried out with different technologies. During In-water Cleaning, fouling will be released as well as antifouling paints which may affect local environment. Therefore, specific measures should be implemented to avoid these issues. For example, Australia has introduced the Antifouling and In-water Cleaning

Guidelines. The Guidelines mention the best practices to followed according to the ship painting age. In addition, the Guidelines introduced decision support tool to mitigate the biofouling spread — for example, addressing the importance of identifying the fouling origin prior performing the operation, in order to decide whether it should be in water operation or in dry dock. Finally, the Australian Guidelines provide measures and requirements about shore-based Antifouling removal and disposal.
Paint manufacturers and developer of in-water cleaning tools are still developing new products to address the main challenges related to hull fouling.

Final information

After completing this work and studying the characteristics of the biofouling phenomenon, it is not possible to determine an ideal antifouling system for all vessels. As described in the study conducted by New Zealand (in chapter IV of this work) each antifouling coating has strengths and weaknesses. Antifouling solutions depends on external factors such as intervals of dry-docking periods, ship speed, the area where it operates and the Fouling attached to its hull. While the trend is towards biocide-free products, their performance are linked to ships' speed and shows poor results at low speed or in case of long periods of inactivity.
On the other hand, SPC systems are quite effective in most ships. However, their high cost and the use of biocides may restrict their use.
Some new technologies promise high effectiveness (e.g. ultrasound or the use of impress currents) but they may generate new problems in the marine environment such as underwater noise.
For the reasons mentioned above, today, it is not possible to recommend a unique antifouling system as effective as the old TBT-based products. Finally, the type of AFS chosen will depend on the characteristics of the ship and its areas of operation.

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