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Dissertation/Thesis

‘’ANTIFOULING & ANTICORROSION METHODS IN SHIPPING IN ACCORDANCE WITH ESG AND IMO REGULATIONS’’

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Summary

The below thesis presents the issue of concentrated marine fouling in vessel's hull and in internal piping and systems of a vessel. Firstly a presentation of the issues that shipping companies are facing is given and what are the consequences if these problems are not addressed in a timely manner.

This is a very significant problem as it affect operational life of vessel and adds significant economic burden due to rise in fuel costs, energy,possible off hire of vessel.

A possible alternative is presented with the introduction of ICCP and MGPS systems as a proactive method and and underwater inspection/cleaning as a reactive method.

The purpose of this thesis is to highlight the steps that are needed to be taken in order for marine fouling to be addressed and included in a possible extension of the already ANNEX environmental regulation and possible adoption of these methods from a class aspect in the beginning of newbuilding vessels as well as in retrofit vessels.

An economic presentation was given both in return of investment in each of the above mentioned, as well as breakdown costs.

The methodology thas was used is a combination of literature review ,data from the existing professional background of the author and adoption of reports that were given from researchers of the field.

From the below analysis ,it is presented the need to tackle amrine fouling in a more organized way by adopting worldwide regulations that will be issued by IMO and are enforced by all countries,port state contols and IACS classes.

Keywords

MGPS,ICCP,Underwater cleaning

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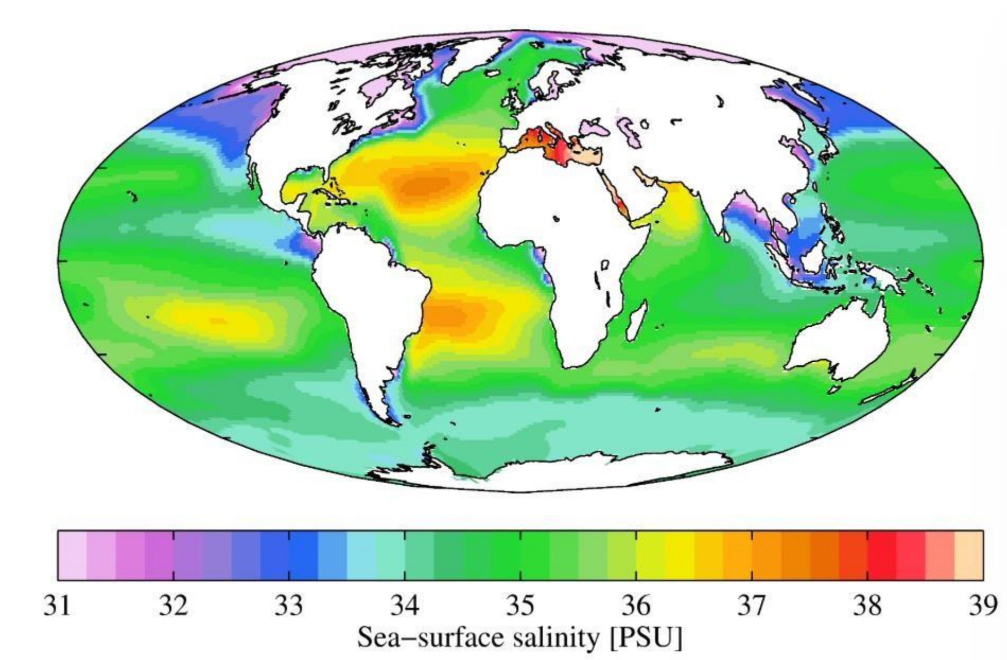
Introduction

One of the biggest challenges in the shipping industry especially in the commercial part of the sector is the constant battle for shipowners to protect vessels from the marine fouling and growing .The main aspect of marine fouling is that due to seawater can enter in any part of vessel and given time it can corrode many parts of the vessel like the hull of the vessel,the piping of the vessel that transports seawater for many functions such as cooling many onboard systems and regulate the temperature of these , used for fresh water via desalination or used in ballast tanks helping in vessel's various operations.
Marine fouling can be ranged and classified whether it is microfouling which are made up from bacteria,diatoms and algae which in many of these have a thin layer and can be invisible to the eye and macrofouling which are larger organisms and grow over time like seaweed,tunicates or barnacles,mussels,tubeworms).The corrosion that the vessel experience over time can affect not only its structure but as time passes by it can also have a significant disruption in vessel's operation and overall costs if not treated correctly and in time. It is such an important aspect in vessel's life cycle that many countries like New Zealand have passed certain laws and regulations on how the vessel should be cleaned and protected in order for vessels to enter their ports.
Marine fouling has strong economic and operational impact in vessel's lifecycle.The fouling alternates the hull surface increasing the hydrodynamic resistance.This event leads to increasing costs(i.e can increase up to 40% in fuel consumption) and at the same time increase carbon emissions which can have serious economical downside due to the new regulations of decreasing carbon emissions in the next years.
Due to the hyrodynamic resistance vessels may need to have more engine power to maintain speed. As we can understand this unnecessary increase in power in several occasion have significant cost in engine's life affecting the planned maintenance and at the same time affecting the voyage times which has significant impact in schedule and operational planning.

Image 1.Vessel's hull and propeller affected by marine fouling(1)

Chapter 1.Corrosion in Vessels

As we discussed above vessels are exposed to sea water and different temperatures as well as different environment conditions.They are categorized in different categories taking into account their content in salt like sodium chloride approximately 3-4% or salt water in rivers or ocean salt water.A very important aspect is that the levels of salt water in oceans everywhere are approximately the same whereas in other seas like Adriatic or Red sea can vary from 3.9% to 4.1% and Baltic sea 1%.So, the content of salt in water directly affects the electrical conductivity of water. (DeGiorgi, V. G., 1970)



1.1 Main factors affecting corrosion

The main factors that affect the corrosion of vessels are the following :
(Abbas, M., & Shafiee, M., 2020; Jirapure, S.C., & Borade, A.B., 2014)

1. Content and diffusion of oxygen
2. Temperature
3. Conductivity
4 Ph
5. Electric Potential

Content and Diffusion of oxygen
Studies have revealed that oxygen is a very important factor in oxidation and the amount of corrosion in vessels is deeply affected by the levels of oxygen in its hull.This diffusion is related also to the amount of water flow, so the diffusion is influenced by the sea depth. If the sea levels are low then the amount of oxygen diffusion is low therefore the corrosion rate is lower. As can understand the hull of the ship is the primary part of the vessel that

comes in contact with the water line so the corrosion happens in a faster rate.Other areas that can show higher corrosion is the stern of the ship caused by waves and rotation of the propeller.
(Jirapure, S.C., & Borade, A.B., 2014).

Temperature
The solubility of oxygen in water is related with the environment's temperature.The diffusion rate is increasing exponentially when increased temperature is applied. For example when a vessel travels through warm or tropical waters this phenomenon is observed whereas the mentioned effects are decreased in colder waters (i.e North Atlantic).Furthermore we can observe that the rate of corrosion is bigger, as the temperature rises that is why the first areas of a vessel that are affected are located near the Engine control room or areas below Bridge.

Conductivity
The conductivity is the ability of a liquid to apply electric current. It is related with the presence of ions or other particles which are electrically charged. Corrosion occurs when the anode and the cathode can directly communicate (i.e a medium).This is the main reason why corrosion is not observed through distilled waters because ions are not present, whereas inorganic salts or dissolved substances move more freely and therefore an electric charge goes through the liquid.Therefore, seawater which has high conductivity is far more corrosive than distilled of fresh water.

Ph
The Ph value is used to observe the levels of acidity or alkalinity and it has a range of values from 1 to 14.When the value is closer to 1 then the liquid is consider as more acid and if it is closer to 14 is consider basic. If the liquid equals to 7 then it is consider as neutral. Ph is very much associated with the occurrence of chemical reactions which can accelerate or slow down the corrosion process of a metal. In a basic liquid where we have alkaline conditions a metal structure is not deeply affected.Sea water has a Ph value of 7.5 so corrosion is the reaction/corrosion in certain materials is less aggressive.

Electric Potential
Every metal which is place in a conductive liquid has a particular electric potential. Therefore the electric potential is measured according to a reference of electrode potential. In that way we can determine the rate of corrosion(Googan, C., 2021).(4)
A more negative potential shows that this specific metals corrodes more easily whereas a more positive shows that the metal has more resistance to corrosion.(i.e if a piece of iron is applied in seawater and measure its potential with the help of a reference electrode, a prediction can be made how much corrosion will affect this metal.

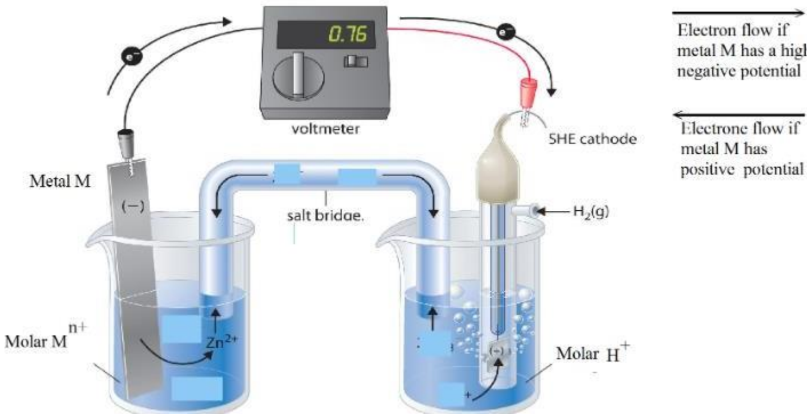


Image. How a metal's rate of corrosion is measured(5)

In order for corrosion to be avoided a first step is the covering of vessel's hull with the appropriate coating in accordance with the IMO regulations to eliminate the contact between seawater and metal structure .It is imperative that the coating applied to the structure does not have empty spaces or imperfections because this will directly affect the friction of vessel and ultimately affect the seaworthyness of the vessel.

2. Application of Cathodic Protection

A very common practice to avoid the corrosion of vessel's hull is the application of cathodic protection.The method of cathodic protection involves connecting an external anode and supplying a continuous electric current to the metallic structure being protected. The structure receives electrons and therefore functions as a cathode. When the electric potential of the ship's hull, which is submerged in the electrolyte (that is, seawater), is adjusted within an appropriate range to ensure that sufficient current is delivered—meaning that the necessary amount of electrical charge is provided—the anodic reactions on the metal surface are suppressed, and the metallic structure (the hull) is fully protected from corrosion.
This practice was invented by chemist and inventor Humphry Dary when in 1761, the english navy requested his assistance for protecting the copper coating of the english vessels.
The first application was on the battleship HMS Samrang were 4 groups of anodes from cast iron were installed successfully and produced great result as far as preventing corossion.However, it was observed that an alarming increasing of marine biofouling was developed on the hull. Ultimately, the beneficial action of copper ions in preventing biofouling was deemed more important than the prevention of corrosion of the sheathing itself, and for this reason the method was abandoned relatively quickly (Von Baeckmann, W., 1997).
At the beginning of the 1900s steel was used widely in the shipbuilding sector due to its better attributes compared to iron and at that time hull corrosion was recognized as a serious problem in the maritime sector.This problem was addressed via the installation of zinc anodes on the stern and rudder of ships.Researches mainly were focused around the development of new alloys for zin and aluminium anodes which were had increasing electrical capacity and potential resulting in better performance .

In the late 1950s the concept emerged that corrosion could be prevented by applying a continuous low-voltage current from an external power source using inert metals as anodes. This approach made it possible to avoid the recurring cost of replacing sacrificial anodes at regular intervals. Consequently, impressed current cathodic protection systems began to be adopted in the maritime industry for the protection of ships and other structures against corrosion.

It should be emphasized that scientific and technological progress in this field has been continuous and remains ongoing. Moreover, as the fundamental theoretical principles governing corrosion become better understood, new methods, materials, and innovations continue to be developed, aiming to enhance the efficiency and effectiveness of cathodic protection systems used in ships.

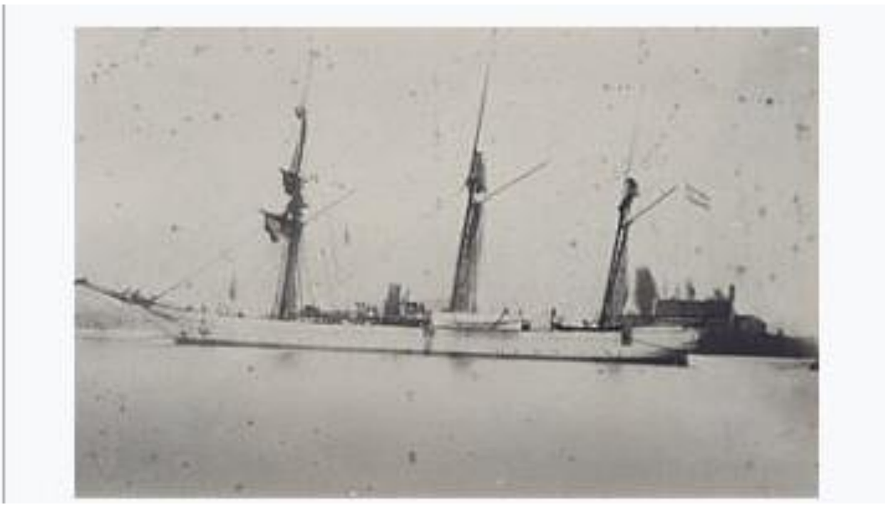


Image: Frigate HMS Samarang

2.1 Consequences of Reduced Protection

When the measured potentials of a vessel do not meet the criteria required for effective cathodic protection, corrosion is expected to be mitigated but not completely halted. The degree of protection achieved depends directly on the amount of current supplied. If the protective current is entirely interrupted, corrosion will soon return to its normal, initial rate.

2.2 **Consequences of Overprotection**

Applying a potential greater than that required for cathodic protection not only results in unnecessary consumption of electrical energy and anode material but may also lead to additional undesirable effects such as:

Detachment of the organic coating:

When the applied protective potential exceeds the maximum allowable value, hydrogen gas is generated. This gas often becomes trapped between the coating and the metal surface, forming blisters and ultimately causing the coating to detach.

Hydrogen embrittlement:

Excessive cathodic protection potential leads to increased hydrogen generation, which reduces the ductility of steel. Hydrogen embrittlement is a hazardous phenomenon, particularly affecting high-strength steels (HQUSACE, 1999).

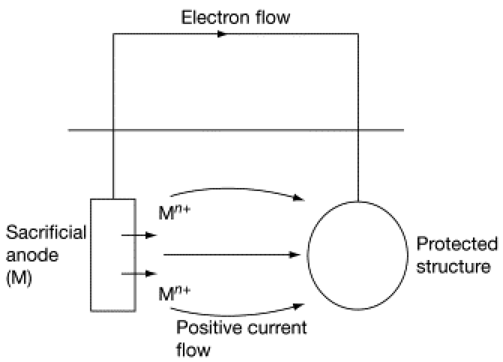
In conclusion, a cathodic protection system must deliver sufficient and properly distributed current to the steel surfaces of a ship's hull so that these surfaces can be polarized within an appropriate potential range defined by cathodic protection criteria. In other words, the design of a cathodic protection system for the external hull must take into account the vessel's operating conditions and geometric characteristics, ensuring that the protective potential is as uniformly distributed as possible across the entire submerged surface. It is evident that the selection of the cathodic protection system plays a crucial role in both the proper functioning and the service life of the vessel (Kakuba, G., 2017; Mrdović, L., & Ivošević, Š., 2023).

2.3 Methods of Applying Cathodic Protection

The principal methods for applying cathodic protection are the following:

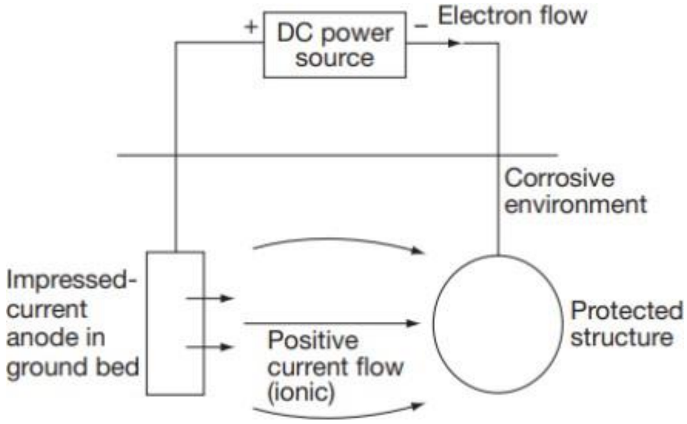
- **Use of sacrificial (galvanic) anodes**
- **Application of impressed current from an external power source**

In the first method, an auxiliary metal is directly connected to the structure that is to be protected, where it functions as the anode. The potential difference between the anode and the steel—determined by their respective positions in the electrochemical series—drives a current through the electrolyte from the anode toward the steel structure, thereby providing protection (Kakuba, G., 2017; Mrdović, L., & Ivošević, Š., 2023).



(Source: Ashworth, V., 2010)

In the second method, an anode made of an inert material is mounted on the surface of the steel hull and connected to an external source of continuous current, which imposes a protective current on the structure .



(Source: Ashworth, V., 2010)

Sacrificial Anode Systems

To understand the operation of sacrificial anodes, it is necessary to refer to the electrochemical series, or activity series, of metals. The metals most commonly used as sacrificial anodes are aluminium (Al), zinc (Zn), and magnesium (Mg), as they are more electrochemically active than steel (an alloy of iron, Fe). As a result, when these metals are electrically connected to steel while immersed in seawater, they supply electrons to the steel surface, thereby protecting it from corrosion (Francis, P.E., 2020; Tezdogan, T., & Demirel, Y.K., 2014).

The service life of sacrificial anodes typically ranges from 10 to 15 years, depending on the amount of current required and the size of the anodes. When a cathodic protection system is properly installed and maintained—through periodic replacement of anodes as needed—the ship’s structure remains protected from corrosion, and consequently, the vessel’s service life becomes dependent on other factors (HQUSACE, 1999).

The sacrificial anode method is primarily preferred for small vessels under 100 meters, where the required protective current is relatively low. It is also widely used for the protection of cargo and ballast tanks, as it is considered safer than impressed current systems. The use of impressed current in such tanks may generate sparks, a hazardous phenomenon when transporting flammable cargo (Veritas, D.N. & Lloyd, G., 2017; Mrdović, L., & Ivošević, Š., 2023).

Required Current Density

To achieve effective cathodic protection, a specific current density must be applied from the power source to the structure being protected. Current density depends on the characteristics of the structure and is expressed as the amount of current per unit area (mA/m^2).

The typical factors that determine the required protective current density include the composition of the electrolyte, the concentration of dissolved oxygen, water flow velocity, temperature, and the condition of the metal surface. For these reasons, the appropriate current density must be supplied according to the environmental conditions and the operating conditions of the vessel. The current density to be applied may be selected using a database of comparable vessels operating under similar conditions or through experimental testing and measurements (ABS, 2017).

During the design of a cathodic protection system, the hull surfaces of a ship may be divided into separate cathodic protection zones. Although these zones are electrically connected, they can be considered independent for design purposes. For example, the hull may be divided into a forward and an aft zone, while the rudder and propeller may be treated as separate zones

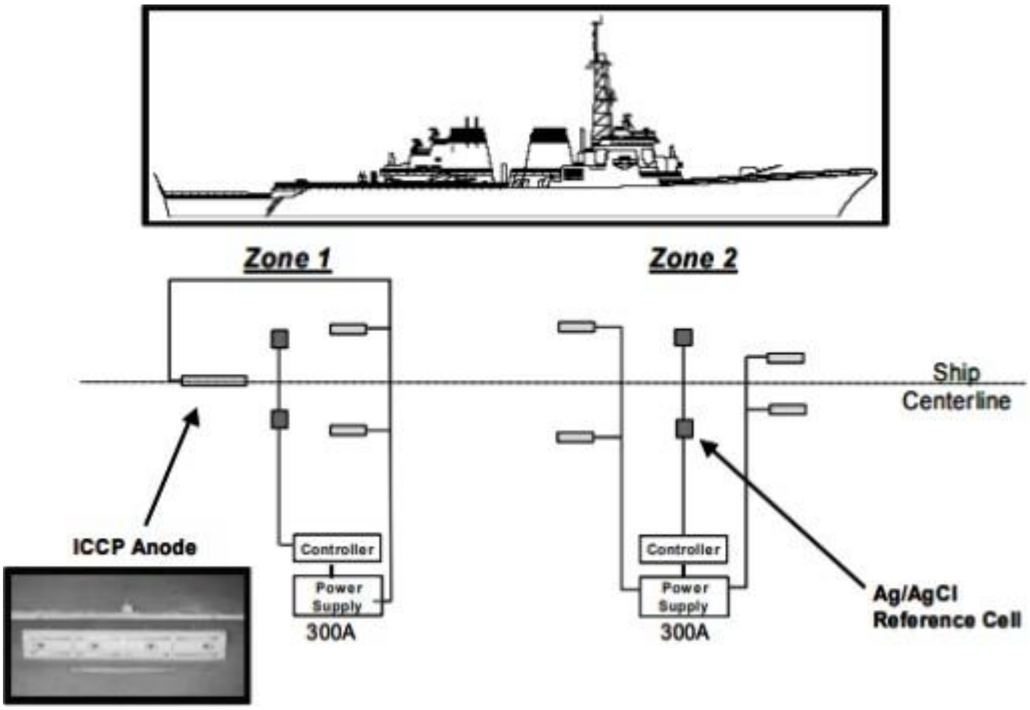


Image: Typical arrangement of a two-zone ICCP system (Source: DeGiorgi, V.G., et al., 2005).

The aft zone typically has the highest current demand due to increased flow rates, turbulence, and the galvanic coupling that occurs between the hull and the propeller. The cathodic protection system for each zone must therefore be carefully designed, taking into account the characteristics of the materials, the surface condition, and the state of the applied coating (ABS, 2017).

3. CATHODIC PROCESS OF IMPOSED CURRENT

3.1 Introduction

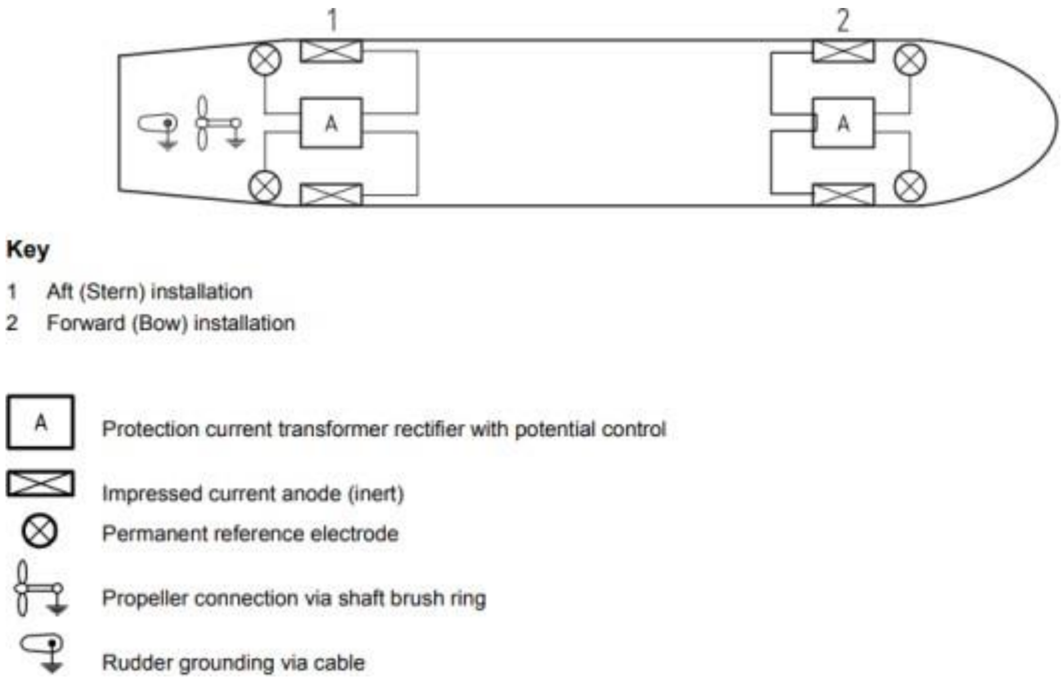
Cathodic protection with impressed current (Impressed Current Cathodic Protection – ICCP) is widely used in both marine and terrestrial applications to prevent corrosion of metallic structures. Unlike sacrificial anode systems, where the required protective current is provided by the natural (spontaneous) potential difference between the anode and the cathode, ICCP systems supply electrons to the protected structure through an external power source.

In an ICCP system, the negative terminal of the power supply is directly connected to the structure to be protected, while the positive terminal is connected to auxiliary inert anodes. Through this configuration, the imposed current ensures that the protected structure remains cathodic, thereby suppressing corrosion processes (Oh & Kim, 2004; Putra et al., 2019).

ICCP systems have become well established in the shipbuilding industry for the protection of ship hulls. Their use is generally preferred for vessels longer than 100 meters, where the required protective current is relatively high and the application of sacrificial anodes becomes economically impractical or technically ineffective. In such cases, the impressed protective current is continuously monitored and adjusted according to the vessel's speed and the electrical resistivity of the electrolyte (seawater). This adaptive control prevents problems associated with both insufficient and excessive protective current, ensuring effective corrosion protection of the metallic structure.

The main components of an ICCP system are as follows:

- Power source
- Monitoring and control system
- Impressed current anodes
- Dielectric shields
- Reference electrodes
- Connection cables
- Cofferdams
- Propeller bonding system
- Rudder bonding system



Visual presentation of ICCP system (Source:European Standard 2012

3.2 Impressed Current Anodes

Anodes used in impressed current cathodic protection (ICCP) systems are designed to be highly resistant to corrosion and to function solely as sources of electrons for the protected structure, without undergoing significant material degradation during the delivery of protective current. Consequently, these anodes do not require frequent replacement, as they are not consumed in accordance with Faraday's law; instead, they experience only minimal material loss, which is generally considered negligible.

However, anodes of this type must also exhibit chemical resistance to the reaction products generated during operation in order to remain effectively inert over their service life. In general, the desirable properties of ICCP anodes include the following (Bohnes & Funk, 1997; Basham et al., 2003):

1. High electrical conductivity.
2. Low rate of mass loss.
3. Adequate mechanical strength to withstand stresses during installation and system operation.
4. High resistance to the elevated current densities imposed on their surfaces.
5. Ease of manufacture and availability in a wide range of shapes and configurations.
6. Low manufacturing cost.

For the cathodic protection of ship hulls, a set of anodes is typically employed, consisting of two anodes of the same type installed on opposite sides (port and starboard) of the vessel, at the same frame number and at an equal distance from the baseline. Specifically, the anodes are installed at least 1.5 m below the vessel's waterline, in a region characterized by reduced hydrodynamic turbulence, in order to minimize the risk of mechanical damage (ABS, 2017).

Furthermore, the number, dimensions, and positioning of the anodes are appropriately determined to ensure the delivery of the maximum required protective current (I_max). This corresponds to the maximum current supplied by the rectifier/transformer unit to which the anodes are connected, enabling the achievement of the required protective potential over the entire area cathodically protected by the system.
The anodes must be fabricated from inert materials and designed for long service life, while also allowing for easy replacement if required. They are commonly manufactured from titanium, niobium, or tantalum substrates coated with a thin layer of platinum, or from mixed metal oxide (MMO) coatings. Anodes may also be made from lead–silver alloys, provided that the anode current density is sufficient to maintain the conductive lead dioxide surface layer.

In general, ICCP systems may employ anodes manufactured from the following materials (Bohnes & Funk, 1997; Basham et al., 2003):

- Cast iron anodes
- Graphite anodes
- Magnetite anodes
- High-silicon cast iron anodes
- Lead–silver alloy anodes
- Platinum-coated anodes
- Mixed metal oxide (MMO) anodes

Anodes vary because of different operating environments,density requirements,mechanical constraints,economic factors and service life expectations.
Different operating environments depending on the salinity of the ocean varying from open water ,brackish water to freshwater.Some anodes (e.g graphite) have better performance results in seawater but poorly in high resistivity environments whereas MMO are effective in a broader range of environments.
Furthermore ICCP anodes need to be resistant in high current densities without rapid degradation. It is well known that large vessels have high current demand therefore there are specific typed of anodes that can be integrated(MMO and platinum coated anodes). On the other hand cast iron and graphite are limited in maximum current density.
Moreover the selection of appropriate anodes is heavily influenced on the different priorities vessel owners may have in regards of the maintenance of their vessel:

-Long dry-dock intervals
-Minimal maintenance
-Easy replacement

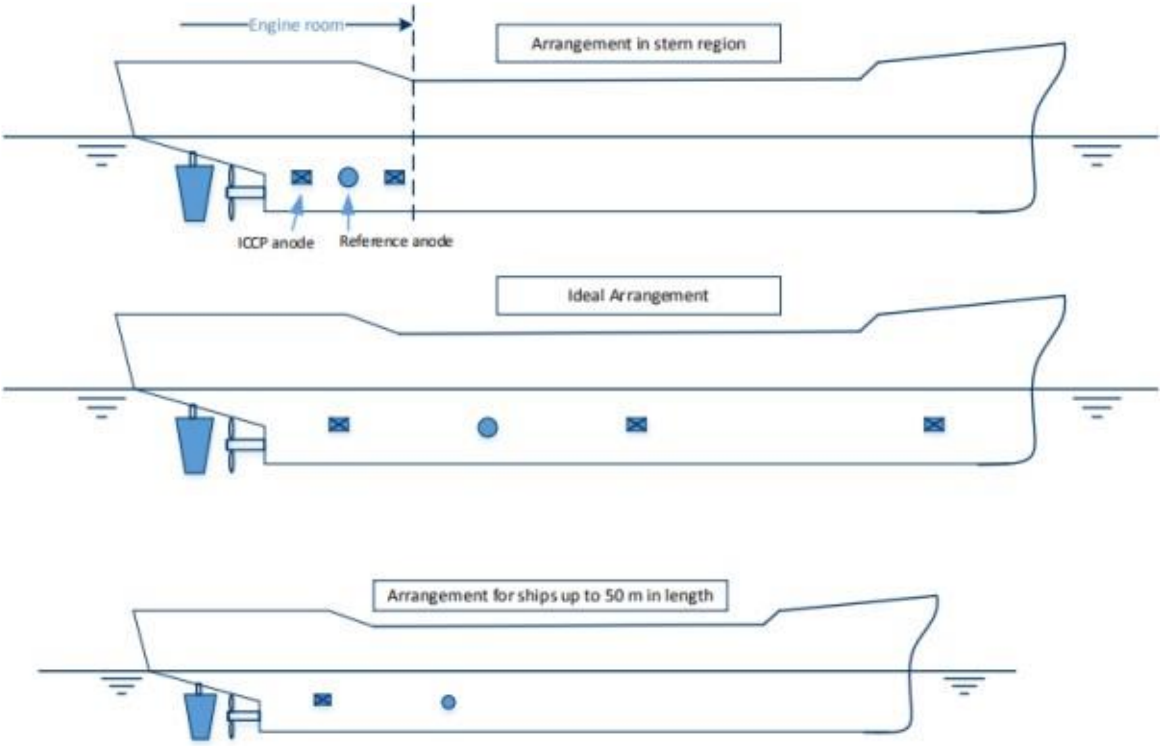
For example MMO and Pt coated titanium anodes have a very long service life, graphite and cast iron are cheaper in cost but their lifespan is shorter and lastly lead and silver can have a very long lifespan but are heavily sensitive to operating conditions meaning meaning vessel's crew maintenance and proper use of system is mandatory to ensure the specific ICCP anodes last. As we can understand there is a constant debate between cost and performance which is heavily influenced by the voyage each vessel is performing along with the proper training of crew to maintain the system in good condition ensuring long lifespan.

Typical Properties of ICCP Anode Materials (Indicative Values)

Anode Material	Consumption Rate (g/year)	Maximum Current Density (A/m^2)	Maximum Operating Voltage (V)
Carbon Steel	7,000–10,000	3–6	50
Graphite	400–700	2–8	50
Magnetite	1.0–3.0	80–120	50
Cast Iron	200–900	20–40	50
High-Silicon Cast Iron	150–400	30–60	50
Lead–Silver Alloy	20–80	200–1,500	24
Platinum-Coated Titanium	0.003–0.015	500–3,500	10
Platinum-Coated Tantalum	0.003–0.015	500–3,000	50
Platinum-Coated Niobium	0.003–0.015	500–3,000	100
Mixed Metal Oxide (MMO) on Titanium	0.0003–0.002	400–1,200	10

3.3 Arrangement of Anodes and Reference Electrodes

The location and arrangement of anodes in impressed current cathodic protection (ICCP) systems are critical to ensuring both their effective operation and their protection against mechanical damage. The optimal arrangement of anodes and reference electrodes (Figure 26) is generally determined based on the calculated current distribution during the system design phase. This calculation takes into account the condition of the hull coating and the expected coating degradation over the vessel's service life. For example, icebreakers and vessels operating in ice-infested waters may experience extensive coating damage in the bow region, resulting in large uncoated surface areas that require increased cathodic protection (ABS, 2017).



Schematic representation of different configurations of anodes and reference electrodes on a ship’s hull. Source: ABS, 2017

With regard to the spacing of anodes in ICCP systems, there is no fixed rule, as both the output voltage and the operating current range can be adjusted according to the specific application. Consequently, anode spacing is determined on a case-by-case basis, based on design calculations and operational requirements rather than prescriptive distance criteria (ABS, 2017).

1. For large vessels with a length of 150 m or more, stern anodes should be installed at a distance of at least 15 m from the propeller. For smaller vessels, this distance may be reduced to approximately 5 m. Reference electrodes should be located at positions where the lowest protective potential is expected, namely at locations farthest from the anodes. On large vessels, reference electrodes should be installed at a distance of 15–20 m from the anodes, with proportionally shorter distances applied to smaller vessels.
2. ICCP anodes are not electrically connected to the rudder; instead, they are positioned between the rudder stock and the ship’s hull. The propeller is protected via a slip-ring arrangement mounted on the propeller shaft
3. The rudder is equipped with galvanic (sacrificial) anodes to ensure adequate corrosion protection.
4. The impressed current cathodic protection system should be symmetrical, meaning that an equal number of impressed current anodes and reference electrodes are

installed in corresponding positions on both the port and starboard sides of the vessel. An asymmetrical configuration may lead to uneven current distribution and localized coating damage.

5. At least one set of anodes should be installed on both the port and starboard sides in the stern region of the vessel, preferably in the vicinity of the engine room.
6. At least one reference electrode should be installed on each side of the vessel. Each reference electrode should be positioned between the anode and the propeller, as far from the anode as practicable. A minimum separation distance of approximately 10% of the vessel's length is generally recommended.
7. Vessels with a length exceeding 175 m should be equipped with a second ICCP system located in the bow region.
8. When an ICCP system is installed in the bow region, the corresponding reference electrode should be positioned between the anode and the bow.
9. Dielectric shielding is required around the anodes to protect the steel hull and to ensure a uniform distribution of the impressed current.

3.4 Bonding of the Propeller and the Rudder

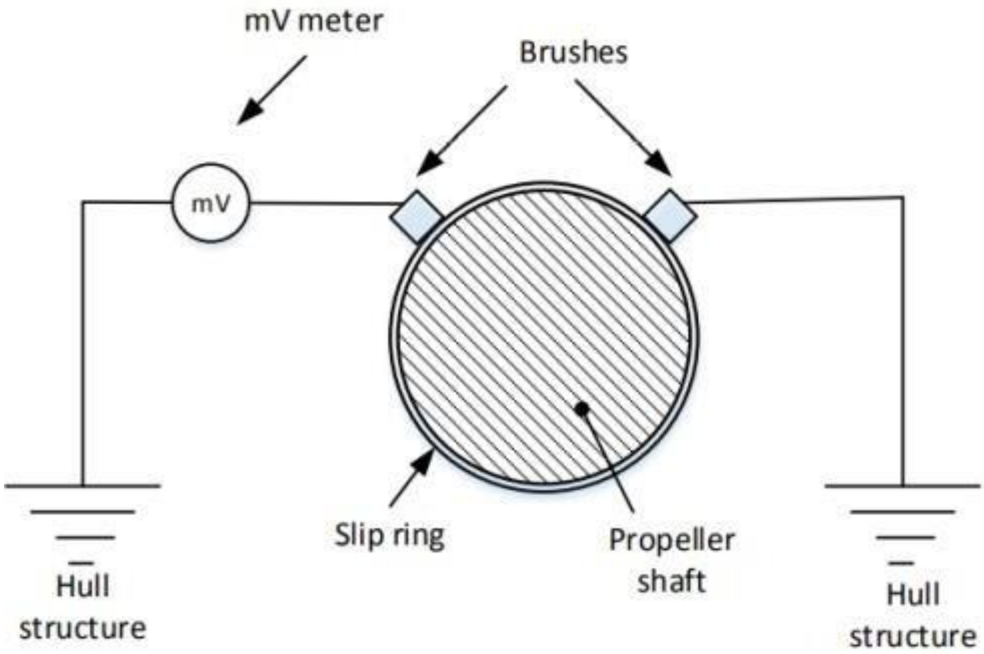
To electrically integrate ship components such as the propeller and the rudder into an impressed current cathodic protection (ICCP) system, a process known as bonding is employed. The purpose of bonding is to establish a common electrical potential between interconnected components and to minimize potential differences that may exist between them.

Bonding connections must exhibit low electrical resistance, as this facilitates effective control and limitation of potential differences throughout the system. Uncontrolled potential differences can lead to undesirable effects, including electrical arcing and corrosion interaction damage. Electrical arcing is a specific form of electrical discharge that may occur when significant potential differences exist between connected components. Corrosion interaction damage may be caused by stray electrical currents that accelerate corrosion processes in the presence of large potential gradients. By ensuring low-resistance bonding, the risk of damage due to electrical arcing and corrosion interaction is minimized, and a relatively uniform electrical potential is maintained along the hull and its appendages.

Bonding of the Propeller

Propellers are typically manufactured from bronze or similar alloys, which exhibit a significant potential difference relative to the steel hull of the vessel. As a result, a **galvanic couple** is formed, which can accelerate corrosion if appropriate cathodic protection is not provided.

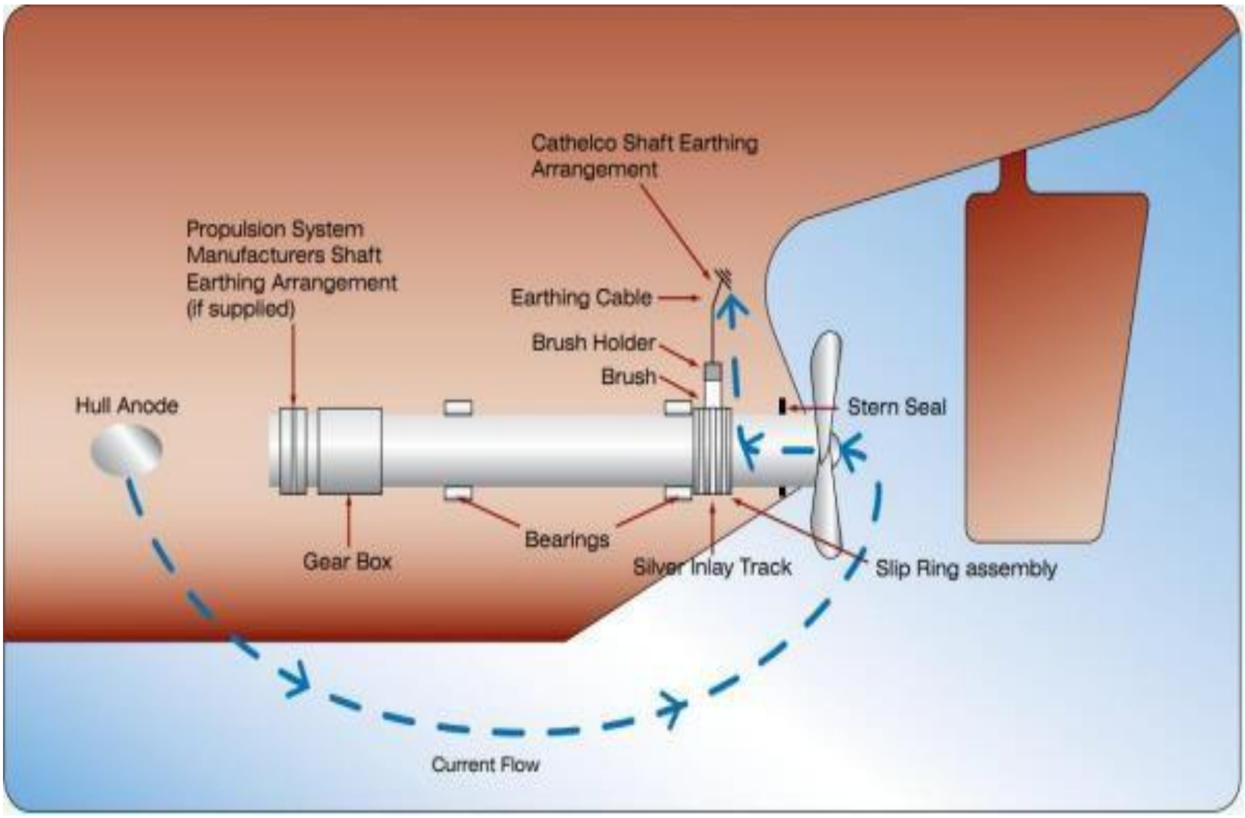
For this reason, shipboard cathodic protection systems must include a shaft grounding system to protect the propeller. In this arrangement, a slip ring is mounted on the propeller shaft to maintain continuous electrical contact with the hull through a set of metallic brushes supported on the slip ring assembly (PTS, 2003).



The effectiveness of the shaft grounding system should be verified by ensuring that the maximum resistance does not exceed 0.001 Ω for water-lubricated bearings and 0.01 Ω for oil-lubricated bearings.
The shaft grounding system includes a pair of high silver/graphite-content metallic brushes, mounted on a fixed support in contact with the slip ring. These brushes exhibit high electrical conductivity, ensuring that the resistance of the shaft bonding system remains low even under adverse operating conditions.
The system also incorporates a monitoring instrument , such as a millivolt-reading voltmeter, to measure the shaft-to-hull potential. The instrument is characterized by high internal resistance, which limits current flow in the circuit and allows accurate measurement of the potential difference between the propeller shaft and the hull. The grounding cables of the monitoring device and the brush assembly must be connected separately.

Slip ring and voltmeter for monitoring the potential difference between the hull and the propeller shaft. (Source: Vasilescu, M., et al, 2019) .

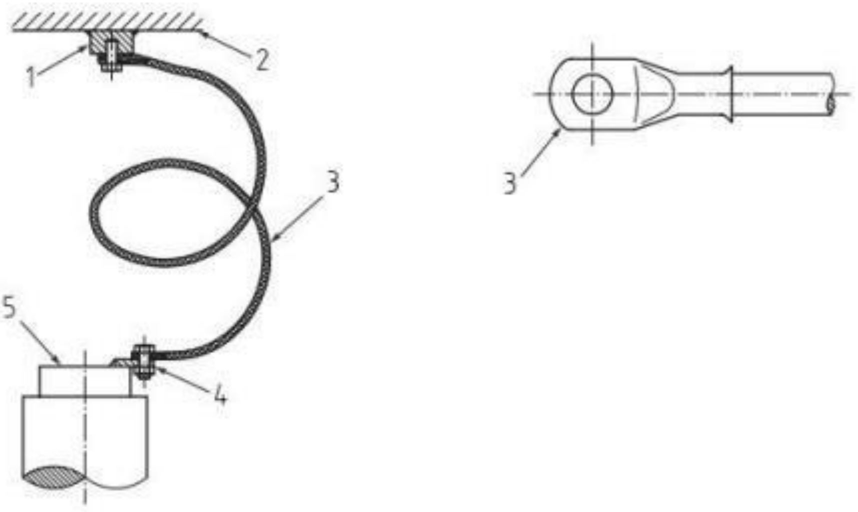
During system operation, a reading of less than 80 mV while the shaft is rotating in seawater indicates effective shaft grounding. If readings exceed 80 mV, the surface of the slip ring should be cleaned. When the shaft is stationary, the voltmeter should indicate 0 mV, since any current entering the propeller should return to the hull.
The bonding system should be inspected at least twice per week, with particular attention to cleanliness. If oil, dirt, or corrosion products accumulate on the slip ring surface or between the slip ring and the shaft, cleaning should be carried out using degreasing agents, fine abrasive paper, and a clean cloth.



Schematic representation of the layout of the ground-based propulsion system. (Vasilescu, M., et al, 2019)

Bonding of the Rudder

In ICCP systems, it is essential that the steel rudder is electrically bonded to the ship’s structure in order to ensure effective corrosion protection



Key

1 Socket for Bolt, brazed or welded
2 Hull internal
3 Ground cable and lug
4 Cable connected to brazed or welded lug on rudder stock
5 Rudder stock

Due to the oscillatory motion of the rudder, a flexible bonding strap or cable is used. One end of the strap is welded to the hull, while the other end is connected to the rudder stock. The resistance of the bonding connection between the hull and the rudder must be sufficiently low to ensure minimal potential differences, typically less than 20 mV.
The flexible bonding strap should have a cross-sectional area of approximately 35 mm², and its length should not exceed 3 m. When estimating the current flow through the bonding connections, both the surface area of the appendage and the maximum current density designed to be supplied by the ICCP system to the hull should be taken into account.
Finally, during system operation, the use of a voltmeter is required to verify the correct functioning of the bonding connections (British Standard, 1991).

4. MGPS (Marine Growth Prevention System)

In the previous chapter it was discussed how the corrossion affects different parts of vessel's hull and how it can be avoided with the use of anodes & ICCP system.Unfortunately corrosion can be detrimental also to many internal parts of the vessel where seawater is passing through vessel's piping system.The seawater is used in a vessel's piping system for the below reasons:

1.Cooling

Cooling is the primary reason because ships generate enormous heat from:
-Main engines
-Generators

-Air conditioning plants
-Refrigeration systems
-Hydraulic systems
-Fuel and lube oil coolers
Therefore seawater is pumped through heat exchanger to remove this heat.
Seawater is ideal because it does not require storage tanks unlike freshwater and allows vessels to run without the use of external cooling sources.
This is the main reason every ship has a sea chest, sea suction and a central cooling system.

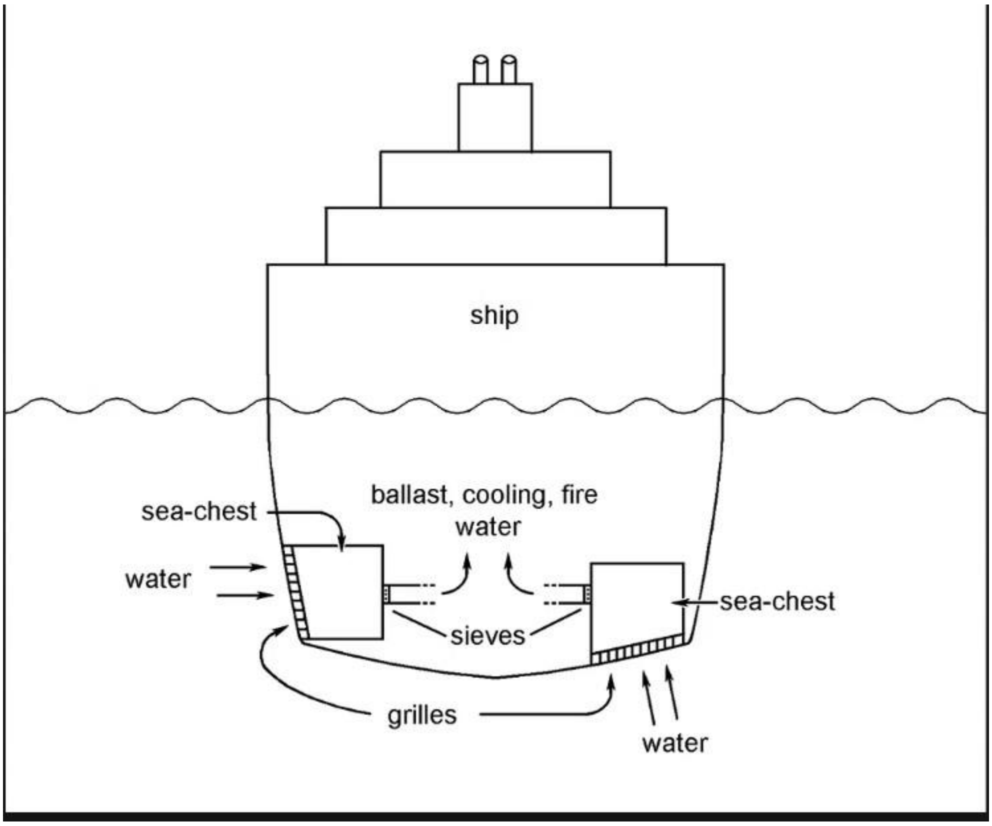


Image.Position and view of sea chest in vessels

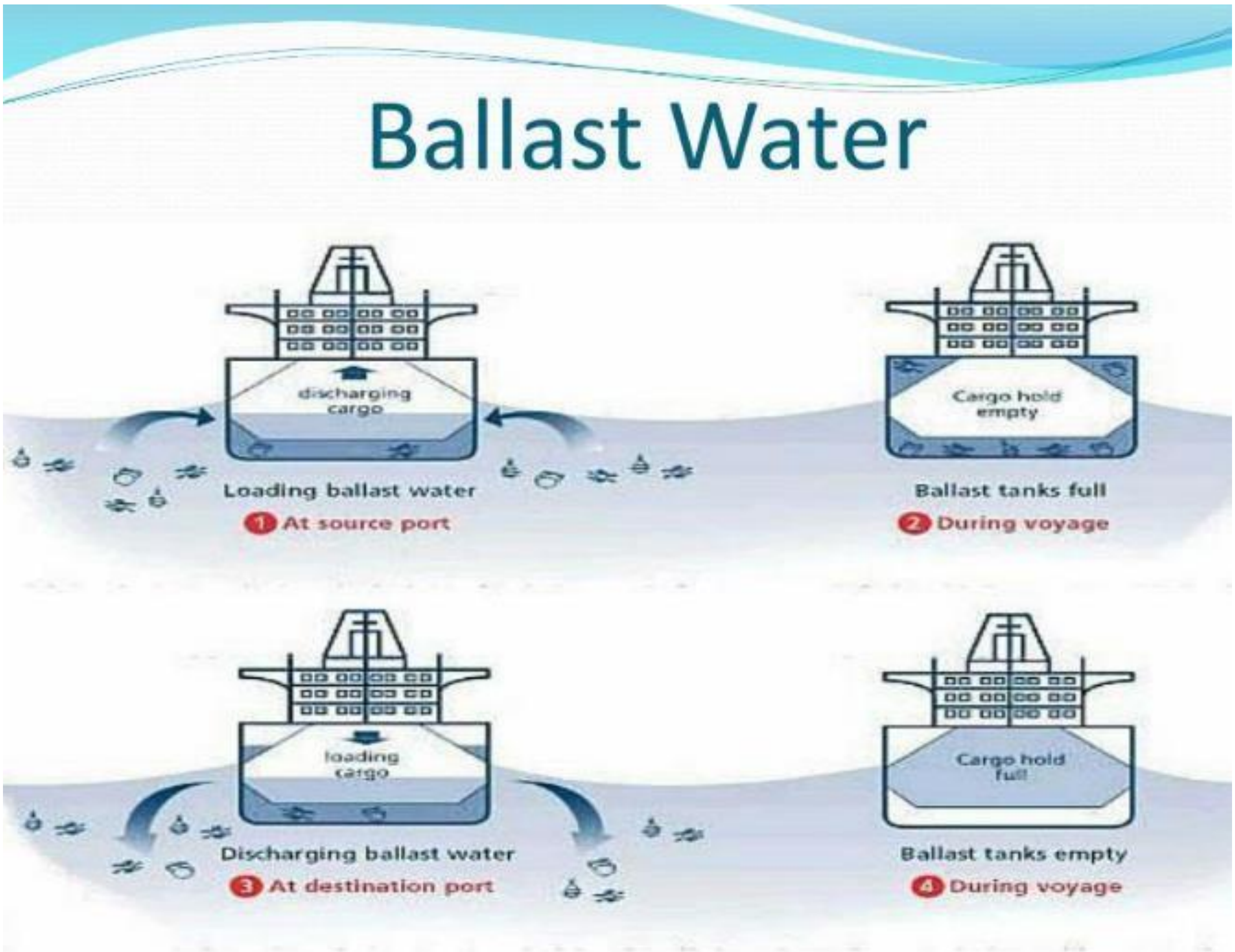
2.Firefighting (Emergency Use)

Seawater is used in
-Fire main systems
-Fire hydrants
-Sprinkled deluge systems (on some vessels)
Because of limitation in freshwater reserves,seawater is the only practical means of firefighting

3.Ballast water

Ships take in seawater as ballast to:
-Maintain stability
-Adjust trim

-Improve propeller immersion
-Ensure safe navigation in different loading condition



4. Sanitary and Utility Systems

Seawater is used for:
-Toilet flushing (on many vessels)
-Deck washing
-Chain locker washing
-General service pumps
Using freshwater for these would be wasteful and require huge storage capacity.

5. Desalination (Freshwater Production)

Seawater is the feedwater for:
-Evaporators
-Reverse osmosis plants

Ships produce their own freshwater from seawater for:
-Drinking
-Cooking
-Showers
-Boiler feedwater
-Technical freshwater systems

In order to avoid the corrosion in the above systems of the vessel ,shipping companies install MGPS (Marine Growth Prevention System) which uses the electrochemical process as it main principal of operation.
Copper anodes under applied DC current are dissolved and produces CU+ ions in the seawater which are very toxic to marine organisms and prevent growth of microoganisms. Moreover it can also promote electrolysis of chloride ions which at a very low current density are enough to prevent growth and not damage the piping of the vessel.

Main Components of MGPS System

-Control Panel (Power & control unit)
-Anodes (Electrodes)
-Reference electrodes (optional but common)
-Cabling and penetration fittings

Control Panel
It can be described as the brain of the system where it converts ship's AC supply (in most vessels 440V or 220V) to low controlled DC output. It regulates the current to each anode based on the seawtaer temperature,the salinity and the flow rate.
Most of the time these systems are equipped with alarms that provide warnings regarding proper functionality of anodes,warinings for adjustment regarding the overcurrent or undercurrent of the system and in case the total malfunction of the system it provides alarm for power loss.
Many times shipowners prefer this system to be integrated to the AMS of the vessel so crew can be aware of any discrepancies that may occur and act fast .

Image. MGPS control panel

Anodes

As mentioned above anodes which are usually of copper and aaluminium material are installed inside the sea chests or at seawater inlets.
Most of the time copper and aluminium anodes are paired for better protection.A very important aspect of the anodes is that a periodic replacement is required to achieve proper functionality of the system.Most of the time if the system is well regulated and maintained they need to be replaced once every 3-5 years.

Image. Copper & aluminium Anodes

Reference electrodes

They provide measurements regarding the actual electrochemical potential in seawater. Additionally they help maintain correct dosing and avoid overproduction. It is important to be mentioned that these reference electrodes are used mainly in automated MGPS systems

Image Reference Electrodes

Cabling and penetration fittings

As we can understand in order for the system to be functions and communicate with different parts of the MGPS it needs to have proper marine approved insulated DC cables along with cable glands and junction boxes to withstand the seawater exposure so electrical safety and system reliability can be achieved

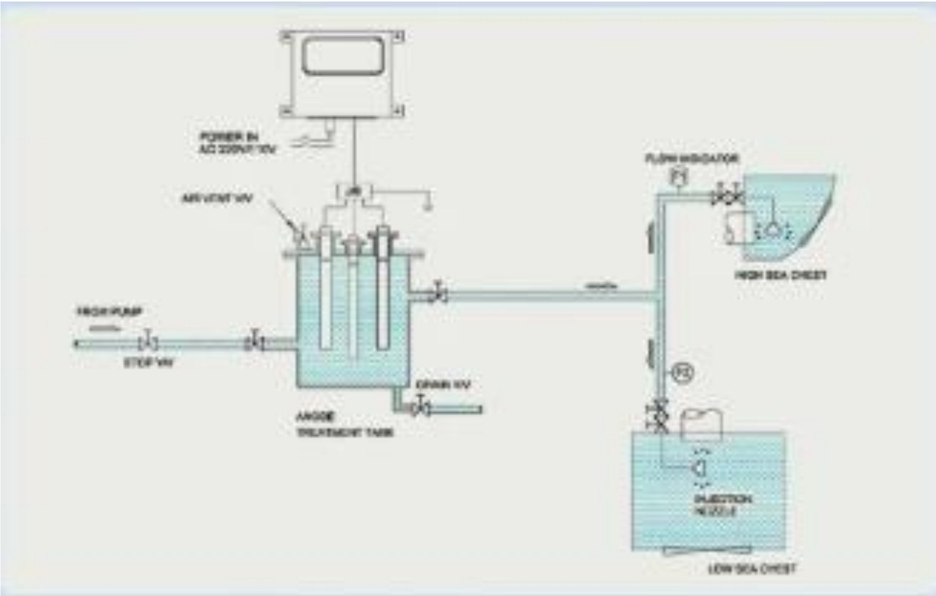


Image. Complete layout of a MGPS system in vessel

As we can understand the main difference of MGPS and ICCP is the different area that each system protects.A clear distinction between the two systems can be provided in the below table

Feature	**MGPS**	**ICCP**
Purpose	**Prevent Marine Growth**	**Prevent Corrosion**
Target	**Seawater systems**	**Hull and underwater fittings**
Mechanism	**Biocide generations**	**Electrochemical polarization**
Anodes	**Consumable**	**Long life MMO (best practice)**
Output	**Copper & Chlorine Ions**	**Protective DC current**

5. Underwater Hull Cleaning

In the previous two chapters ICCP and MGPS systems can be considered both proactive as they try and tackle corrossio and marine growth to a certain extent before microorganisms start to accumulate in a vessel's hull.

Shipping companies in order to eliminate any marine growth which has accumulated once or twice a year perform underwater hull inspection or cleaning.Many shipping companies provide reports for the underwater operations overall in a year as this often provides insights in savings in fuel cost ,maintenance and in general avoiding extra costs from vessel operation.The IMO in general provides guidance on how to perform underwater cleaning but these guidelines are not enforced but rather encouraged to be followed by shipping companies (*Marine Growth Prevention: Best Practices for MGPS Systems in Modern Shipping)*

In-Water Cleaning Operations

In-water cleaning may be carried out as part of the Biofouling Management Plan (BFMP) when biofouling is detected during scheduled inspections . All cleaning activities should be conducted safely and responsibly, avoiding unnecessary wear or damage to coatings and minimizing the release of waste materials. Cleaning must comply with all applicable local regulations and requirements, including obtaining approval from the relevant authority when necessary.
Cleaning systems with capture capability may be used to remove microfouling or macrofouling, as they generally pose lower environmental risks than systems without capture. Cleaning without capture should only be carried out when permitted by local regulations and in a location approved by the relevant authority, and only under the following conditions:
• On ship areas with a fouling rating below 2; or
• On ship areas with a fouling rating above 1, provided that the BFMP and Biofouling Record Book (BFRB) demonstrate, to the satisfaction of the relevant authority, that:
• the area is coated with a non-biocidal hard coating in good condition; and
• the biofouling accumulated in the same waters

The selected IWCS should be appropriate for the ship’s type, BFMP, operational profile, and availability (e.g., time at berth or anchorage), as well as the cleaning location and prevailing environmental conditions (such as wave surge, wind, flow velocity, weather, and visibility).
and secondly be compatible with the surface material, coating type, and fouling rating of the areas to be cleaned For uncoated areas (e.g., propellers, anodes), the system should be suitable for the fouling rating present. It is imperative to avoid causing unnecessary wear or damage to coatings, taking into account the type and extent of biofouling.

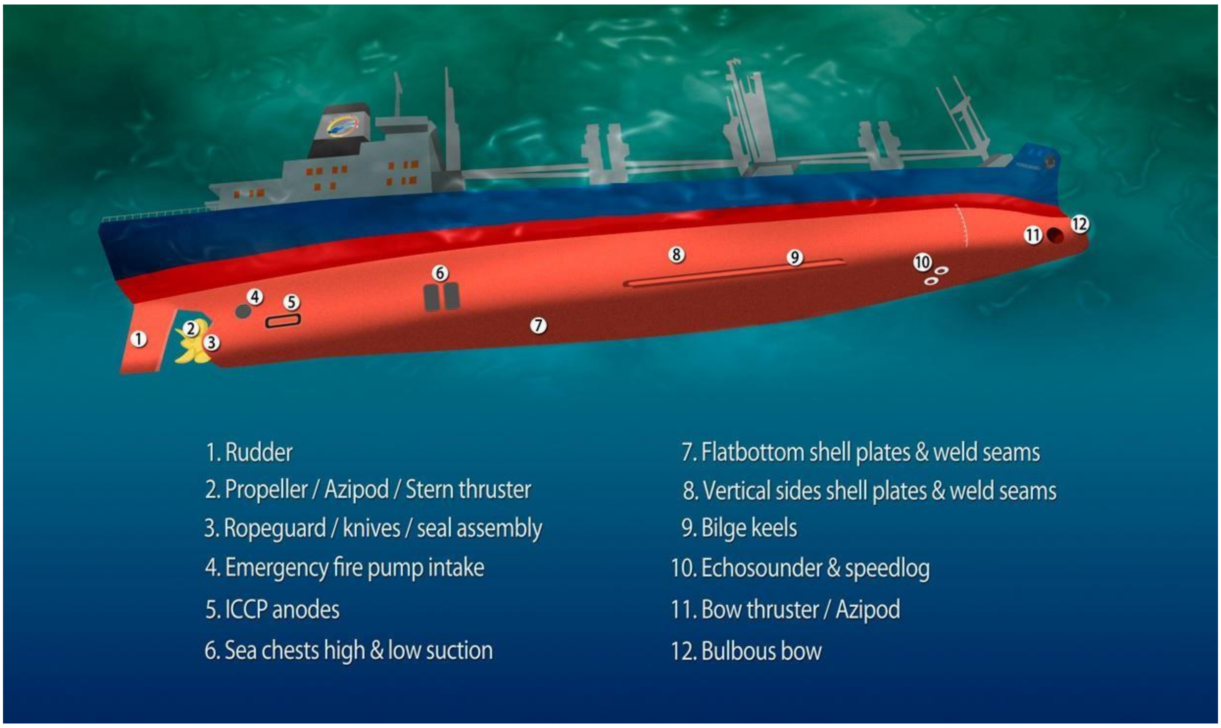


Image. Areas of underwater Hull Cleaning

In the last few years a number of countries have established their own plan for underwater cleaning operations and the extent of marine biofouling on vessels’s hull that it is allowed for ships to enter their ports.
Most recent acts are the Australian & New Zealand standards that are now implemented and the Brazilian Standards which will be implemented in June 2026.

Rating	Description	Surface coverage	Action required
 0. No fouling	Surface entirely clean. No visible biofouling.	-	-
 1. Microfouling	Submerged areas partially or entirely covered in microfouling. Metal and painted surfaces may be visible beneath the fouling.	≤ 1%	Proactive cleaning may be recommended.
 2. Light macrofouling	Presence of microfouling and multiple macrofouling patches. Fouling species cannot be easily wiped off by hand.	1% to 15%	Cleaning with capture is recommended. It is recommended to shorten the interval until the next inspection. If the anti-fouling system (AFS) is significantly deteriorated, dry-docking with maintenance and reapplication of the AFS is recommended.
 3. Medium macrofouling	Presence of microfouling and multiple macrofouling patches.	16% to 40%	
 4. Heavy macrofouling	Large patches or submerged areas entirely covered in macrofouling.	41% to 100%	

In the above photo according to brazilian standards vessels can enter brazilian ports only in the condition of 0 or 1 rating .Otherwise underwater hull cleaning needs to be conducted prior vessel’s arrival in Brazilian regions.

Areas of the vessel that need to be thorough clean and treated before entering Brazilian or Australian ports are the below:
-Vertical Sides
-Flat bottom
-Propeller
-Niche areas
-Rudder

In the below table Similarities and differences between the IMO guidelines for antifouling management and Brazilian & Australian Standards can be observed. *Australian Government (In water Cleaning Guidelines) & GUIDANCE ON IN-WATER CLEANING OF SHIPS' BIOFOULING IMO April 2025*

Topic	**IMO**	**Australian Standards (DAFF)**	**Brazilian Standards (NORMAM-401/DPC)**
Main Goal	**Reduce invasive species globally.**	**Protect Australian waters from foreign species.**	**Protect coastal ecosystems.**
Approach	**Flexible**	**Very strict and precautionary.**	**Strict but varies by port.**
Permission	**Follow local rules.**	**Approval always required.**	**Approval required.**
BFMP	**Required**	**Required.**	**Required.**
Record Book	**Required.**	**Required.**	**Required.**
Environmental Controls	**Minimize waste release.**	**Zero discharge allowed.**	**Strict controls; port-specific**
Inspections	**Regular inspections advised.**	**Frequent inspections; sometimes mandatory.**	**Required; varies by port.**
Niche Areas	**Important focus.**	**Strong focus.**	**Must be included in plans.**
Enforcement	**Advisory, not mandatory**	**Very strict enforcement.**	**Moderate to strict.**
Flexibility	**High.**	**Low.**	**Medium.**

IN-WATER CLEANING REQUEST FORM

This form can help relevant authorities apply the *2023 Guidelines for control and management of ships' biofouling to minimize the transfer of invasive aquatic species* (resolution MEPC.378(80)) and process cleaning requests in their jurisdiction. For more information about this form, please refer to the *Guidance on in-water cleaning of ships' biofouling* (MEPC.1/Circ.918, as may be amended).

A - TO BE COMPLETED BY THE MASTER ON BEHALF OF THE SHIPOWNER/OPERATOR			
GENERAL INFORMATION			
Proposed location of cleaning Click here to enter text.		Proposed date of cleaning Click here to enter a date.	
SHIP INFORMATION			
Name of ship Click here to enter text.	Flag Click here to enter text.	IMO Number, Official Number (if applicable), or other distinctive number or letter Click here to enter text.	Type of ship Click here to enter text.
Shipowner or operator or ISM Company Number (if applicable) Click here to enter text.	Ship's agent Click here to enter text.	Length overall Click here to enter text.	Beam or ship's breadth Click here to enter text.
Choose the best description for the ship's operating profile: ☐ Domestic ☐ Transoceanic ☐ International coastal ☐ Other, please specify: Click here to enter text.			
ATTACHED DOCUMENTATION			
Which of the following are included in this request? Select all that apply: ☐ Biofouling Management Plan ☐ Biofouling Record Book ☐ International Anti-fouling System Certificate ☐ Photos or videos from recent inspection ☐ Reports from previous cleanings ☐ Documentation from recent inspection ☐ Ports of call since the last complete cleaning (including dates and locations of any stationary period over 7days) ☐ Other, please specify: Enter text.			
BIOFOULING INFORMATION			
Date of delivery, last complete cleaning or dry-docking (whichever is more recent) Choose an item. Click here to enter a date.		Date of last underwater hull inspection Click here to enter a date.	

Type of fouling in area that will be cleaned ☐ Microfouling ☐ Macrofouling	Origin of fouling ☐ Same waters ☐ Other (if same waters, provide supporting information)	By percentage, estimated amount of the ship covered in macrofouling Click here to enter text.
PRIMARY COATING INFORMATION		
Manufacturer Click here to enter text.	Type/name of commercial product Click here to enter text.	Primary biocidal compound (if any) Click here to enter text.
Date of application Click here to enter a date.	Remaining service life (in months) Click here to enter text.	Did most recent inspection find the coating in good condition? ☐ Yes ☐ No
Area of application ☐ Whole hull ☐ Other, please specify: Enter text.	Does the ship have more than one coating? ☐ Yes ☐ No	Details of secondary coating (if any) Click here to enter text.
MASTER'S DECLARATION		
I certify that the information listed in section A is true and correct		
Name of master Click here to enter text.	Signature Click here to enter text.	Date Click here to enter a date.
Email: Click here to enter text.	Phone number: Click here to enter text.	

<table>
<tr><th colspan="6">B - TO BE COMPLETED BY THE SERVICE PROVIDER</th></tr>
<tr><th colspan="6">CLEANING SPECIFICATIONS</th></tr>
<tr><td colspan="3">Manufacturer and model of IWCS to be used:
Click here to enter text.

Date the relevant authority gave approval to operate (attach documentation):
Click here to enter a date.</td><td colspan="3">Type of service:
☐ Cleaning with capture
☐ Cleaning without capture

Will niche areas be cleaned? ☐ Yes ☐ No</td></tr>
<tr><td colspan="6">If performing cleaning with capture, are particles over 10 μm separated from the effluent during treatment?
☐ Yes ☐ No ☐ N/A</td></tr>
<tr><td colspan="6">If particles smaller than 10 μm are separated from the effluent during treatment, to what size (in μm)
Click here to enter text.</td></tr>
<tr><td colspan="6">Type of secondary treatment is used to reduce the risk of introducing non-native organisms:
☐ None ☐ UV ☐ Chemical ☐ Heat ☐ Other: Enter text.</td></tr>
<tr><td colspan="6">Is the cleaning plan attached to this form? ☐ Yes ☐ No</td></tr>
<tr><th colspan="6">COATING COMPATIBILITY</th></tr>
<tr><td colspan="6">Does information provided by the coating manufacturer establish that the cleaning methods and techniques are suited to the coating and that there are no contraindications to cleaning? ☐ Yes ☐ No, explain: Click here to enter text.</td></tr>
<tr><td colspan="6">Does guidance provided by the IWCS manufacturer establish that the IWCS has been independently tested on the coating, or the type of coating, used on the ship? ☐ Yes ☐ No, explain: Click here to enter text.</td></tr>
<tr><td colspan="6">What information establishes that the actual condition of the coating and fouling rating are suitable for cleaning using the IWCS?
☐ Information submitted by the ship ☐ Completed pre-cleaning inspection
☐ Pre-cleaning inspection to be done during cleaning
☐ Other, explain: Click here to enter text.</td></tr>
<tr><th colspan="6">SERVICE PROVIDER DECLARATION</th></tr>
<tr><td colspan="6">I certify that the information listed in section B is true and correct</td></tr>
<tr><td colspan="3">Name of service provider
Click here to enter text.</td><td colspan="3">Name of staff
Click here to enter text.</td></tr>
<tr><td colspan="2">Job title
Click here to enter text.</td><td colspan="2">Signature</td><td colspan="2">Date
Click here to enter a date.</td></tr>
<tr><td colspan="3">Email: Click here to enter text.</td><td colspan="3">Phone number: Click here to enter text.</td></tr>
</table>

<table>
<tr><th colspan="4">C - TO BE COMPLETED BY RELEVANT AUTHORITY</th></tr>
<tr><td>☐ Cleaning request approved</td><td>☐ Cleaning request rejected</td><td>☐ Need more details - resubmit</td><td>☐ Postpone cleaning</td></tr>
<tr><td colspan="4">Notes: (Any conditions of approval. Reasons why a cleaning request was rejected, needs resubmission, or has been postponed.)
Click here to enter text.</td></tr>
<tr><td colspan="2">Name of relevant authority
Click here to enter text.</td><td colspan="2">Name of staff
Click here to enter text.</td></tr>
<tr><td>Job title
Click here to enter text.</td><td>Signature</td><td colspan="2">Date
Click here to enter a date.</td></tr>
</table>

(GUIDANCE ON IN-WATER CLEANING OF SHIPS' BIOFOULING IMO April 2025)

In general the main reasons for performing underwater inspection and underwater cleaning can be summarized and viewed below :

1. Assessing Hull and Coating Condition

- Identify coating wear, blistering, delamination, or corrosion.

- Evaluate the effectiveness of antifouling or hard coatings.
- Plan maintenance or recoating schedules more accurately.

2. Checking for Structural Integrity

- Inspect for cracks, dents, deformation, or weld failures.
- Detect early signs of metal fatigue or impact damage.
- Verify the condition of sea chests, bilge keels, rudders, and stabilizers.

3. Propeller and Shaft Condition Monitoring

- Identify cavitation damage, pitting, or imbalance.
- Check for entanglement (ropes, nets, debris).
- Ensure smooth operation and prevent vibration issues.

4. Verifying the Condition of Niche Areas

- Inspect bow thrusters, stern tubes, gratings, anodes, and intake grids.
- These areas often accumulate fouling faster and may require targeted maintenance.

5. Monitoring Cathodic Protection Systems

- Check the condition and consumption rate of sacrificial anodes.
- Verify the performance of impressed current cathodic protection (ICCP) systems.

6. Damage Assessment After Grounding or Collision

- Determine the extent of underwater damage following an incident.
- Support insurance claims and repair planning.
- Ensure the vessel remains seaworthy.

7. Compliance With Class, Flag, and Port Requirements

- Some inspections can substitute for dry-dock surveys under certain conditions.
- Required for class renewal, intermediate surveys, or port state control checks.

8. Pre-Purchase or Charter Condition Surveys

- Provide an objective assessment of underwater condition before sale or charter.
- Helps buyers or charterers evaluate vessel value and operational readiness.

9. Environmental Monitoring

- Check for accidental discharges, hull leaks, or coating failures.
- Monitor marine growth patterns for biofouling management planning.

10. Ensuring Operational Readiness

- Confirm that underwater components (e.g., thrusters, rudders) are functioning properly.
- Identify issues that could affect maneuverability or safety.

6. Return of Investment (ROI) of ICCP ,MGPS Systems & Underwater Cleaning

In the past chapters we described the usage of the above systems in vessel’s cycle of life from an environmental and operational aspect . These systems provide significant economic benefits. In this chapter we will present the return of investment (ROI) from these systems keeping in mind that values may differ due to different vessel’s size,different pricing from maker and difference in cost benefit due to different levels of operational management from each owner.

Return of Investment (ROI) & Cost Benefit of ICCP

ICCP systems are used in many business sectors but there is a significant growth in the last years in shipping industry and it is expected to have an overall grow across different industries for up to 5,22% mainly in the Asia Pacific region according to PW consulting Automotive & Machinery Research Center . *(PW Consulting Research Center -Impressed Current Cathodic Preotection System Market)*

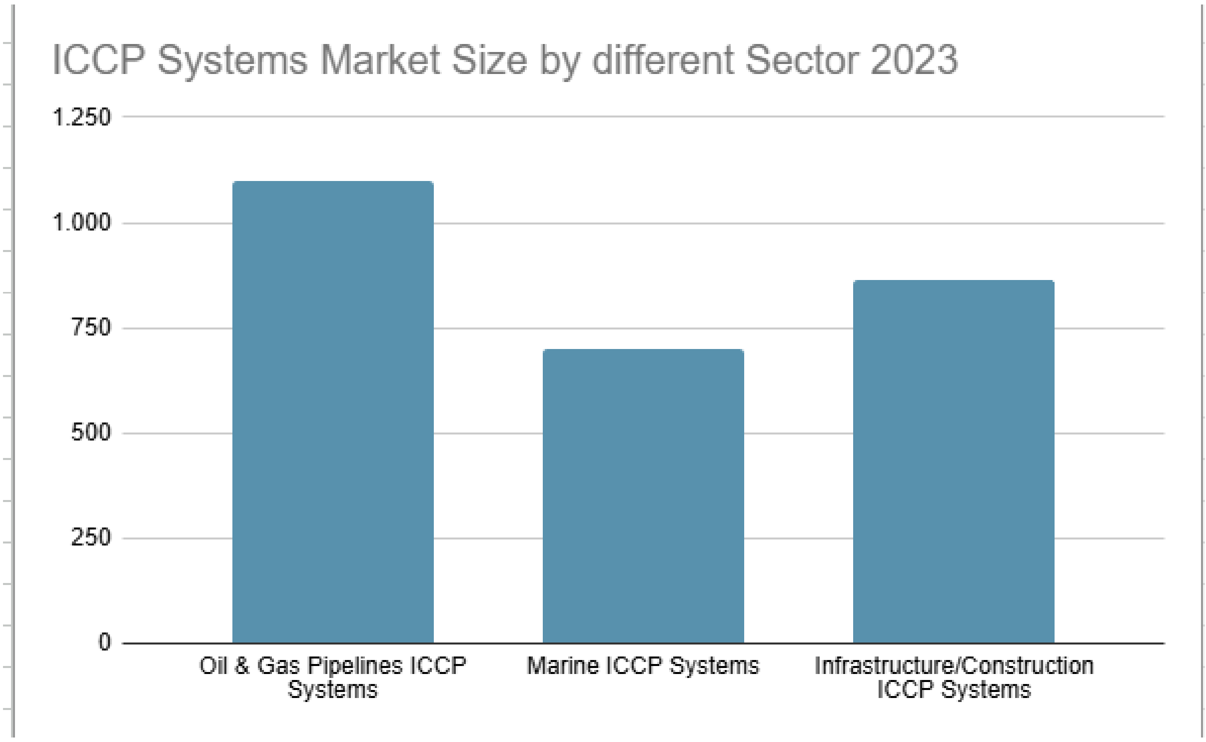
Moreover the forecast by 2030 is 3.82 Bn USD across different sectors

In the following tables provided by PW consulting Automotive & Machinery Research Center we can observe the growth of ICCP systems in different sectors and upcoming years.

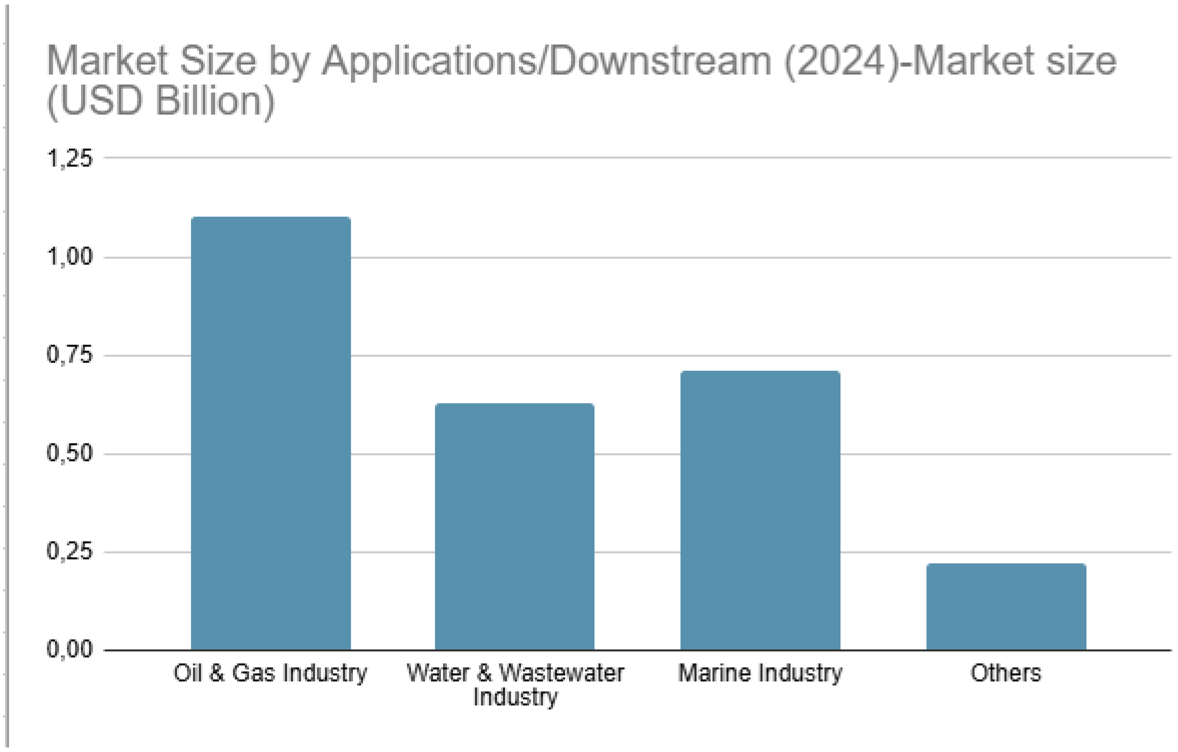
Year	Global Market Size in USD Billion
2023	2,67
2024	2,81
2025	2,96
2026	3,11
2027	3,27
2028	3,44
2029	3,61
2030	3,82

Table. Global Market size and Growth Forecast

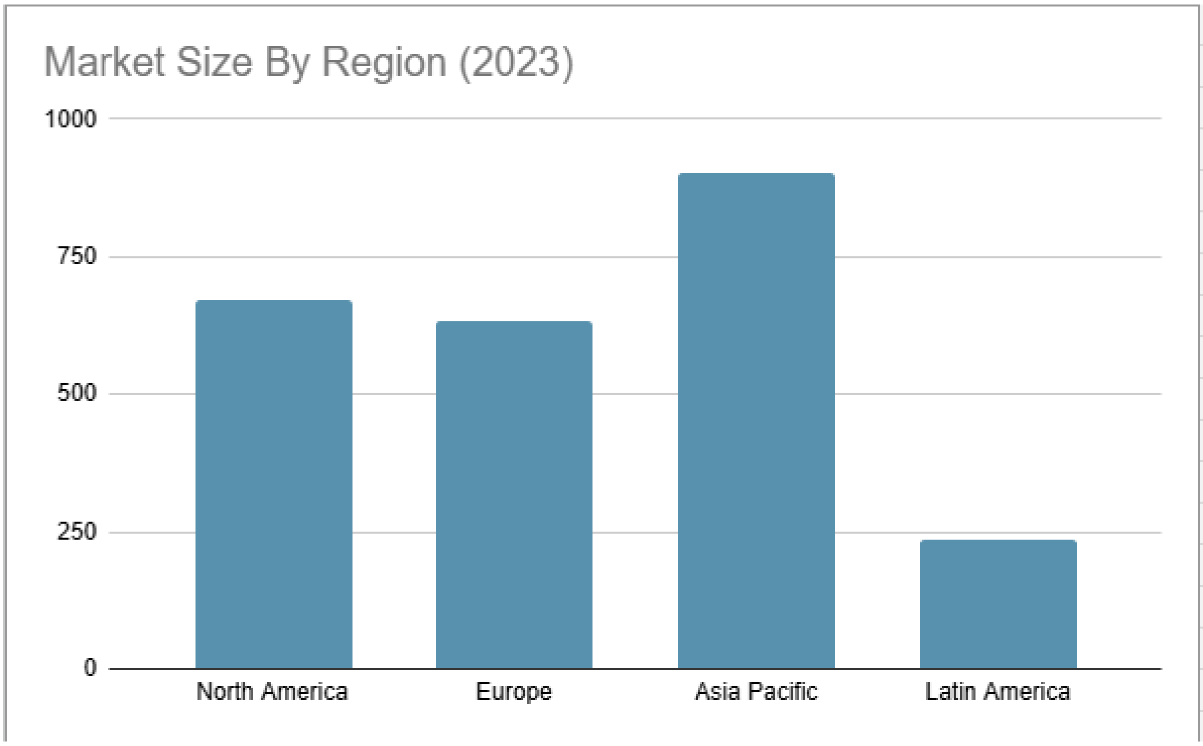
It is important to notice that shipping/marine industry is the third industry in size that has adopted this system as we can see in the next table.(9)



Furthermore these systems have an overall diversified use that are used in different sectors that sometimes are part of the marine/shipping industry. In the next graph we can observe how these systems play a significant role in Oil & gas industry but also in water and wastewater industry. *(PW Consulting Research Center -Impressed Current Cathodic Preotection System Market)*



Lastly, as we mentioned in the beginning of this chapter the growth of ICCP systems is significant in the Asia-Pacific Region.



In commercial vessels in the shipping industry figures vary depending on vessel’s size ,manufacturer and commercial reasons so an overall range estimation can be given and not an exact figure.

Below we can see a list of the many components of an ICCP system from a major distributor, and observe an estimation of an ICCP new installation in a vessel. Prices can vary depending on the manufacturer and the overall pricing policy of each maker and service company.

	300 AMPERE MMO/Ti STRIPE ANODE ASSEMBLY	2	PCS	1290.00	2580.00
	PURITY ZINC REFERENCE ELECTRODE CELLASSEMBLY	2	PCS	260.00	520.00
	100AMPERE RECESSED MMO/Ti CIRCULAR ANODE ASSEMBLY	2	PCS	530.00	1060.00
	PURITY ZINC REFERENCE ELECTRODE CELL ASSEMBLY	2	PCS	260.00	520.00
	EPOXY PUTTY 60LTRS AS PER	20	LTR	45.00	900.00
	GREASE FOR FWD COFFERDAMS	20	LTR	6.00	120.00
KCS0014	HIGH DENSITY SILVER GRAPHITE BRUSH	3	PCS	100.00	300.00
KCS0022	SHAFT MONITORING SINGLE BRUSH HOLDER	1	PCS	35.00	35.00
KCS0032	SHAFT GROUNDING DOUBLE BRUSHHOLDER	1	PCS	55.00	55.00
KCS005	SILVER ALLOY SHAFT SLIP-RING	1	PCS	1096.00	1096.00

Total installation costs excluding labour costs are approximately 7,186$ USD.
If we add labour cost with an conservative approach then the added lumpsum cost for a retrofit during a drydock period is 1800$USD resulting in an overall labour & spare parts cost of 8,986$ USD.

No	Part No.	Description	Qty	Unit	Unit Price	USD Amount
	MAKER:					
1		Lumpsum cost technical service	1	TIME	1800.00	1800.00
2		Shipyard management fee and/or boarding pass cost	1	TIME	AUCTUAL	
					TOTAL:	1800.00

Below is an approximate pricing range for different sizes of vessel for ICCP systems:
-Small vessel: ~ $2,000 – $5,000
-Medium vessel: ~ $5,000 – $12,000
-Large vessel: ~ $12,000 – $25,000+

The advantage of ICCP system is that during drydock installation time takes 5-7 days for a standard vessel and required minimal maintenance and check of reference electrodes every 2-3 years.The added cost would be the inspection and panel calibration which usually is done every 12 months and it is performed by a certified engineer

According to Cathodic Marine Engineering *(Cathodic Marine Engineering PTE LTD- Impressed Current Cathodic Protection Systems)* the return of investment is delivered from various savings:

Reduction in Coating Maintenance Costs	50%-70%
Drydock Intervals	Saving 300K $USD-500K $USD per cycle
Reduced fuel Consumption from smoother Hulls	3-5% efficiency gain

Over a vessel's 25 year lifespan,the total savings can exceed 2-3$ million USD.

For example if we consider the below data for Bulk carrier

-Daily fuel consumption: ~25–35 ton/day (heavy fuel oil)
-Operating days per year: ~200–250 days
-Fuel price estimation: ~$500–$700/tonne
According to the above values ICCP reduces fuel use by a modest 3–5 % through smoother hull resistance.A modest 3% fuel reduction of 25 ton/day at 600USD/ton results in 0,75 ton/ per day saved resulting in annual savings of 90,000$USD and in 25 years lifespan of 2,250,00 $USD.
Lastly if we consider the same data for a bulk carrier a 5% reduction then the annual savings accumulate in 150,000$USD :aand for a 25 year lifespan accumulates in 3,750,000$USD.

Return of Investment (ROI) & Cost Benefit of MGPS

The Growth of and adoption of MGPS has significantly increased in the past years.
As per reports of Market Reports World *(Marine Growth Prevention Systems (MGPS) Market Size, Share, Growth, and Industry Analysis, By Type (Anti-fouling systems, marine growth prevention technologies), 2026)* the significant increase is observed mainly in Asia Pacific with a 35% of global MGPS installations with retrofits over 1,500 commercial vessels.Also Europe after the adoption of new biofouling and ballast control legislation accumulates 25% of MGPS deployments.

The main cost savings factors from the installation of MGPS as per Cathodic Marine Engineering (*Cathodic Marine Engineering PTE LTD Marine Growth Prevention: Best Practices for MGPS Systems in Modern Shipping 2026)* are the following for a typical large vessel:

Eliminated Chemical Treatment Costs	$25,000-$40,000
Reduced heat Exchanger Cleaning	$30,000-$50,000
Improved fuel efficiency 2%-4%	$20,000-$40,000
Avoided Emergency Repairs	$15,000-$30,000
TOTAL ANNUAL SAVINGS	**$90,000-$160,000**

As we can observed the above table is a range of cost saving factors because those numbers are influenced by vessel type, how well the system is operated by the crew and how well it is maintained .One additional element that needs to be addressed is that the total savings can go even higher due to the fact that owners avoid the use of drydock that would put significant cost from an operational aspect .

Furthermore the payback period for the installation is 6-12 months for most vessels and in case vessel is trading in low fouling areas it can have a payback period of 1-2 years.

MGPS system offer several additional economic benefits which are the following:
-Reduced maintenance as operators report 20–30% lower maintenance costs with MGPS installed.
-Biofouling can reduce heat exchanger performance by **up to 50%**, causing overheating and breakdowns.

ROI Calculation and Lifecycle cost analysis

1) **System parameters for a large vessel (tanker/container/bulk carrier):**

MGPS installation cost	$70,000
Lifetime	15 years
Anode replacement	Every 3 years
Annual inspection of control panel	(price ranges according to service provider)

2) **Annual Operating Costs of MGPS**

Cost Item	Frequency	Cost
Anode Replacement	Every 3 years	$6,000
Control Panel Maintenance	Yearly	$,1500
Electricity Consumption	Yearly	$500

So for the above parameters the average annual MGPS operation cost is:
2000+1500+500=4,000$/year so a total operating cost ≈ $4,000/year.

The net annual Benefit is calculated by the following:
Annual savings-Annual operation cost=120,000-4,000=116,000

We need to point out that for the above calculation we imported the median value of the cost saving range

ROI Calculation

$$ROI = \frac{Net\ annual\ benefit}{Initial\ investment}$$

So if we divide the initial investment=70,000 with the net annual Benefit=116,000 ,we get a ROI=166% per year.

Payback Period

$$Payback = \frac{Investment}{Net\ annual\ benefit}$$

So if we divide the initial investment with the net annual benefit we get Payback=7 months which falls in the range as described above 6-12 months

Lifecycle Cost Analysis (15-Year Ship Life)

Cost component	Value
Initial Installation	$70,000
Anode Replacement(5 times)	$30,000
Maintenance & electricity	$30,000

If we add the above values then the Lifecycle cost is $130,000.
So for a vessel's lifecycle the total savings are approximately $1,8 million.
Finally the net lifecycle benefit is 1,800,000-130,000=1,670,000.

Return of Investment (ROI) & Cost Benefit of Underwater Cleaning

As we have mentioned in past chapters ICCP and MGPS systems act as proactive methods in protecting each system but underwater cleaning act as a reactive method.Sooner or later marine fouling will need to be removed from vessel's hull especially in cases were vessel has not traded for a while or if it trades in warm waters where marine fouling concentration is sped up. In general shipping companies perform up to 2 times a year underwater cleaning operations but there are several occasions that they might only perform underwater inspection (to check vessels hull, class surveyor matters, ship purchase/sale etc.).
The cost of of underwater cleaning is heavily influenced in the region that it will be performed,the size of the vessel ,the parts of the vessel that will be cleaned and the type of underwater cleaning.For example the cost of an underwater cleaning in Egypt/Fujairah area is significantly cheaper in regards of USA ,Japan/Korea area or ARA region. Furthermore if vessel trades in Australia/New Zealand region vessel needs to be cleaned according to the standards of these countries (as we have mentioned in previous chapters)

in order to be accepted in the respective ports of the region.
In the below pictures we can observe the different cost of underwater cleaning operations in different parts of the world:

SUBJECT: MV TBN (LOA 290m, Beam 45m) / ETB: 17th Mar., Kwangyang

WORK ORDER : UW Cleaning as per AUS requirement			
NO.	**ITEMS**	**AMOUNT (USD)**	
1	Mob/Demob	$	2,600
2	UW photo report as per AUS requirement - photo only	$	3,000
3	UW hull cleaning - Vertical side (Portside & Starboard): 7,400 USD	$	17,400
	UW hull cleaning - Flat bottom: 7,400 USD		
	UW hull cleaning - Sea chest: 1,300 USD		
	UW hull cleaning - Niche area (Rope guard, Rudder): 1,300 USD		
4	Propeller Polishing	$	2,500
5	Diving boat (1ea * 3 days): 1,500 USD/boat/day	$	4,500
	Total (Excluding V.A.T)	**$**	**30,000**

Terms and Conditions :

1. Work confirmation(PO) to be issued at least 3 days in advance due to diving work permit processing.
2. Additional charges apply for heavy fouling (hard marine growth >50% coverage and >10 mm height)
   - The agreed amounts for ITEMS No. 1, 2, and 3 shall be secured, even if the planned tasks are not completed by the scheduled date due to slow progress caused by heavy fouling.
   - Heavy fouling charges shall be 50% of the "UW hull cleaning" rate per additional day.
   - Additional diving boat charges due to heavy fouling shall be applied on a daily basis.
3. Above waterline(boot-top) hull cleaning can only be performed up to 0.5m above waterline.

Image .Cost of Underwater cleaning in Korea per Australian Requirements

Ship Name: TBN **Date of Quotation:** 27 OCTOBER 2025
Client: BPCO **Date of Job:** TBD
LOA: 225.00 METERS **Location:** GALVESTON FAIRWAY ANCHORAGE

As per your request we are pleased to provide the following price estimates for diving services.

Hull Cleaning (Vertical Sides) - Up to 12 hours from SGS Portal to SGS Portal $7,500.00

Please note the area around the bilge keel (1 meter above and 1 meter below) and the water line area usually cannot be completed at an unsheltered anchorage due to movement of the vessel. If weather permits, it can be attempted but it is not guaranteed.

- Cleaning of vertical sides from bow draft marks to stern draft marks 1m above the bilge keel and a single pass 1m below the bilge.
- Cleaning of intake grates on external surfaces.
- Bilge keels, bulbous bow, tunnel thrusters, stern tube, rudder, or areas not accessible with SGS equipment can be quoted separately.
- Photos taken before and after with written report.
- Cost estimate is based on normal/soft growth.
- 25% Surcharge for Heavy Growth (barnacles or excessive calcium)

Hull Cleaning (Flat Bottom) - Up to 12 hours from SGS Portal to SGS Portal $10,000.00

Please note the area around the bilge keel (1 meter above and 1 meter below) usually cannot be completed at an unsheltered anchorage due to movement of the vessel. If weather permits, it can be attempted but it is not guaranteed.

- Cleaning of the flat bottom from the keel out to the turns on port and starboard sides on all areas of the hull that remain flat.
- Photos taken before and after with written report.
- Cost estimate is based on normal/soft growth.
- 25% Surcharge for Heavy Growth (barnacles or excessive calcium)

Propeller Polishing – Up to 8 Hours from SGS Portal to SGS Portal $3,850.00

If heavy calcium or hard growth is present, it may prolong the length of the propeller polishing and reduce the time available to perform the swim out of the hull within 8 hours.

- Two stage micro-polish on all blade faces.
- Single stage polishing of propeller hub.
- Photos taken before and after with written report.
- Swim out of hull with photographic report of accessible areas *(if possible, within quoted hours).*
- Cost estimate is based on normal/soft growth.
- 25% Surcharge for Heavy Growth (barnacles or excessive calcium)

Ship Name: TBN **Date of Quotation:** 27 OCTOBER 2025
Client: BPCO **Date of Job:** TBD
LOA: 225.00 METERS **Location:** GALVESTON FAIRWAY ANCHORAGE

General Hull Inspection - Up to 8 hours from SGS Portal to SGS Portal $3,850.00

- Photographic hull inspection.
- Written report in accordance with SGS standard service report template.

Dive Station per day $500.00

Workboat Per Day (Day Rate Excluding Fuel/Lube & Sustenance) $5,000.00

- Fuel/Lube and Sustenance will be billed at actual cost plus 15%
- Crane charges for loading/offloading $750.00 per 2 hours minimum
- Customs Clearances (if required) $460.00 per roundtrip to vessel

Image. Cost of Underwater Cleaning in USA region

VESSEL	IMO	LOCATION
TBN	TBA	GIBRALTAR

DESCRIPTION	QTY	RATE	AMOUNT
Underwater Photo Inspection to determine state of fouling and condition of vessel's hull. ETC 1-2 hrs	0	1,800.00	0.00
Vertical sides cleaning, including rudder ETC 6-8 hrs.	0	5,510.00	0.00
Flat bottom cleaning ETC 4-6 hrs.	0	5,850.00	0.00
Propeller polishing to Rubert Scale Grade A. Based on a #4 Blades x 6.1m. diameter. (extra blades and PBCF will incur on a surcharge of 25% of the quoted price -per extra blade + PBCF) ETC 2-4 hrs	0	2,650.00	0.00
External cleaning of sea grids (@170GBP per grid)	0	170.00	0.00
Full underwater cleaning (Inspection, Flat bottom, vertical sides, rudder and up to #5 sea grids cleaning). ETC 12-14 hrs.	0	8,300.00	0.00
Full underwater cleaning with propeller polishing (Inspection, Flat bottom, vertical sides, rudder and up to #5 sea grids cleaning. and propeller polishing) ETC 14-16 hrs.	1	9,500.00	9,500.00
Entanglement Removal 650 GBP Per Hour or Part Therefore	1	650.00	650.00
Cleaning of Bilge Keels 550 GBP Per Hour or Part Therefore	1	550.00	550.00

Acceptance of this quotation also constitutes acceptance of the attached Terms and Conditions

TOTAL **GBP 10,700.00**

Image. Cost of Underwater Cleaning in Gibraltar Region

In the above pictures we can observe the difference in pricing in different regions.Shipping companies and chartering companies take this part in careful consideration once voyages are planned in order to plan accordingly and minimize costs. The above prices are often influenced by percentage of marine fouling,possible surcharges and number of teams that need to be mobilized for each case.

Therefore if we need to calculate the Return of investment ROI [13]we need to take into consideration fuel savings, cleaning cost, and how often fouling builds up. We need to take the generic formula and apply it to our case:

$$\mathrm{ROI} = \frac{\text{Net benefit}}{\text{Cost of investment}} \times 100$$

So, in our case Net Benefit is annual saving minus annual cleaning cost and cost of investment is the price of underwater cleaning.

$$\mathrm{ROI} = \frac{\text{Annual savings from cleaning} - \text{Annual cleaning cost}}{\text{Annual cleaning cost}} \times 100$$

So if we take into consideration the below inputs:

Vessel fuel burn: 25 t/day
Fuel price: $650/t [14]
Operating days: 250/year
Fouling penalty avoided by periodic cleaning: 6%

Underwater cleaning cost: $30,000 per cleaning
Number of cleanings: 2/year
(A Practical Guide to the selection of energy efficiency -Technologies for ships-2022)

Then Fuel savings:
25×650×250×0.06=243,75025

Annual cleaning cost:
30,000×2=60,00030 (per two times /year)

Net annual benefit:
243,750−60,000=183,750243 divided by 60,000 ,the ROIis 306% annually

Payback period

$$\text{Payback} = \frac{\text{Cleaning cost}}{\text{Monthly savings}}$$

Monthly savings :243,750/12=20,312.5243
For one $30,000 cleaning: 30,000/20,312.5≈1.48 months

Cost-benefit for underwater hull cleaning is usually positive when fuel savings from reduced fouling exceed the cleaning cost and any off-hire/port-time cost.

A practical framing is:

$$\text{Net benefit} = \text{fuel savings} + \text{other benefits} - \text{cleaning cost} - \text{operational side costs}$$

The main benefit is lower drag. IMO materials explain that biofouling increases hull roughness, which increases hydrodynamic drag; the immediate result is either loss of speed at constant power or higher power demand to maintain speed.

For the benefit side, GreenVoyage2050 says fouling may easily increase fuel consumption by 10% to 20%, and even more in severe cases if not addressed. A ScienceDirect source in turn reports underwater cleaning can reduce fuel consumption by about 10.1% in one cited operational context.

For the cost side, one literature source says underwater cleanings typically cost about US$10,000 to US$30,000, depending on hull area cleaned and technique used, and may require one to three days in port. *(Economic analysis of ship operation using a new antifouling strategy Y. Wu, J. Hua, D.L. Wu, Ocean Engineering,Volume 266, Part 4,2022)*

So the economic rule of thumb vessels with meaningful fuel burn, even a modest avoided fouling penalty can outweigh a five-figure cleaning bill fairly quickly. GreenVoyage2050 also notes that the fuel-consumption increase from biofouling can exceed the gains from many retrofit energy-efficiency technologies, which is why cleaning often has a strong business case.

$$\text{Annual fuel savings} = \text{daily fuel burn} \times \text{fuel price} \times \text{operating days} \times \text{fuel penalty avoided}$$

$$\text{Annual net benefit} = \text{annual fuel savings} - \text{annual cleaning cost} - \text{off-hire/port impact}$$

$$\text{ROI} = \frac{\text{annual net benefit}}{\text{annual cleaning cost}} \times 100$$

If a vessel spends $500,000/year on fuel, and underwater cleaning avoids just 10% of fouling-related fuel waste, that is roughly $50,000/year in fuel savings. If cleaning costs $10,000–$30,000, the gross benefit can still be attractive before counting off-hire and local compliance costs. That inference follows directly from the fouling penalty and cleaning-cost ranges above.

The above figures are indicative as we mentioned and are heavily influenced by vessel size,trading patterns, method of cleaning in order to protect vessel's hull and coating and port stay for each case. (*INTERNATIONAL CONVENTION ON THE CONTROL OF HARMFUL ANTI-FOULING SYSTEMS ON SHIPS 2001, IMO 24 October 2024*)

7.ESG in Shipping

In previous chapters we provided an economic analysis of the MGPS,ICCP and underwater cleaning operations.These figures are often included in ESG reports produced by shipping companies in order to provide an overall view of the sustainability of their company.It covers a broad field of areas as ESG are initials for Environment, Social and Governance.
In the following table we can see what each sector covers:

E – Environmental	S – Social	G – Governance
Greenhouse gas emissions (CO_2)	Crew welfare and safety	Corporate ethics and anti-corruption
Energy use and fuel efficiency	Labor rights and working conditions	Board structure and transparency
Pollution (air, water, marine)	Diversity and inclusion	Compliance with laws and regulations
Biodiversity and ecosystem impact	Community impact	Risk management

Usually ESG reports are produced by shipping owners annually and it is often required to access capital loans and investment as it is heavily requested from investors,banks and finance. *(DNV ESG In Maritime)* &(*Moore ESG in Shipping)* .

The mentioned systems (MGPS & ICCP) and underwater cleaning operations are mainly focused in the Envronmental and Governance aspect of the ESG reports as their goal is to reduce fuel use and costs therefore reduce pollution (air,water,marine), protect the biodiversity and comply with with laws and worldwide regulations (IMO, Brazilian Standards, Australian and New Zealand standards).
Usually in the ESG reports the above systems are not mentioned specifically but are embedded under broader ESG categories such as:

-Energy efficiency measures
-Emissions reduction strategies
-Operational efficiency improvements
-Maintenance practices affecting environmental impact

As we can understand ESG reports are mainly used as a strategic and financial tool rather than a technical manual. More and more Greek Shipping companies are producing ESG reports like TEN *(TEN ESG Report 2024), (AEGEAN Shipping ESG Report 2023)*some generate these reports on their own or they appoint this task to other organizations like Moore.

8. Conclusions-Results

In this thesis a description of the systems and their usage in the shipping industry was introduced.The main goal of this thesis firstly is to point out the necessary steps that need to be taken in order for vessels in the future to have a more sustainable approach which derives from cutting fuel costs,energy but at the same time keep vessel operationally effective.

MGPS and ICCP systems although are not class mandatory ,after their installation need to be class approved and checked. It is a safe and good alternative in order to cut costs as we mentioned above.Many shipping companies are starting to incorporate these systems in their reports. On the one hand results are based on limited data as these technologies are adopted in last few years and secondly many of the results are case sensitive and shipping companies are reluctant to give them to third party companies or researchers.
Nevertheless ,the figures and common practices of manufacturers and engineers of these systems prove that this is a good alternative in order to tackle marine fouling in vessels.
A good solution would be that these type of systems would be fully class mandatory from the beginning of vessel's life and be part of marine fouling report.

Regarding underwater cleaning operations ,indeed IMO provides general regulation guidelines which are not mandatory but rather urge shipping companies to follow these guidelines.Proof of how necessary is to have a more strict regulatory framework is that many countries like Brazil,Australia,New Zealand are producing their own rules for marine antifouling which are very strict. The opinion of this thesis is that IMO should incorporate all these guidelines into an existing ANNEX for the environment to help shipping companies have a common framework and avoid different regulations from different countries which many times cause operational difficulties in vessel's trade routes.

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