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Review paper

The role of environmental factors in ship hull maintenance

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Abstract

This paper explores the critical influence of environmental factors on the maintenance of ship hulls, which are vital for maritime operations. It examines how variables such as water temperature, salinity, air humidity, and biological factors like marine biofouling affect the integrity and longevity of hull materials. Through a comprehensive analysis of case studies and empirical data, the study identifies the correlation between environmental conditions and the frequency of maintenance interventions required to prevent degradation. The findings highlight the necessity for tailored maintenance strategies that consider specific water conditions to enhance hull performance and reduce operational costs. Ultimately, this research contributes to the development of best practices for ship maintenance, emphasizing the importance of environmental awareness in maritime engineering and management.

Keywords: Environmental condition; Maintenance; Ship hull; Operation.

1. Introduction

The maritime industry is a vital component of global trade, with millions of tons of cargo transported across the world's oceans every day. However, the harsh marine environment poses significant challenges to ship hull maintenance, with corrosion, fouling, and other forms of degradation threatening the structural integrity of vessels. This paper will examine the critical role of environmental factors in ship hull maintenance, highlighting the impact of seawater, temperature, and other environmental conditions on hull integrity. Maintaining

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a ship's hull is crucial for ensuring safety, performance, and longevity. Some studies have been conducted to show how the environmental factors play significant roles and how often and how thoroughly this maintenance needs to be done. From saltwater corrosion to marine growth, the conditions a ship faces can greatly impact its hull's condition (Caldwell and Constantinis, 2013).

The increasing demand for sustainable and eco-friendly products has led to a significant shift in the coatings industry, with water-based coatings emerging as a popular alternative to traditional solvent-based coatings. Water-based coatings, which utilize water as a solvent instead of volatile organic compounds, have gained widespread acceptance due to their reduced environmental impact and improved health and safety profiles. However, the performance and durability of water (Chavan and Sethi, 2025).

By understanding these elements, you can take smarter actions to keep your ship in top shape. Let’s dive into how the environment shapes the way that are suitable for maintaining the ship hull. Thus, this paper tries to represents the key environmental factors affect ship hulls, how these factors accelerate wear and damage, and what practical steps are needed to protect and maintain the marine vessels.

1.1.Climatic conditions of corrosion

These conditions include two factors: air temperature, water vapor content, solar radiation, etc. Other factors are conditioned by the first ones, and indicate the extent to which they will affect the corrosion of certain materials, for example, microbiological pollution of the atmosphere. Corrosion depends on the pollution of the atmosphere by these organisms and their biological activity. Of course, these factors depend on the first ones, for example, temperature and humidity. Other factors also include atmospheric pollution in industrial zones (e.g. ozone formed at places where insulation sparks are caused by the first ones, water vapor in the air). However, each microlocation has its own specific corrosion properties that are aggressive for certain materials, and these influential factors should be used when choosing protection methods. Some very close areas may have different climatic factors, so detailed knowledge of the conditions in individual microlocations is necessary (Chen *et al*., 2022).

1.1.1 Effect of temperature

Increasing temperature accelerates chemical reactions, especially oxidation. Furthermore, the insulation coefficient of certain materials decreases with increasing temperature. Temperature jumps during a day or a short interval are also important. Electrical characteristics in particular change with temperature changes (Gao *et al.*, 2024).

1.1.2 Effect of air humidity

Humidity causes swelling of organic materials. The period in which the humidity changes is important, because sudden changes have a particularly harmful effect. The material absorbs moisture, causing hydrolytic destruction, or it condenses on the surface, seeps into pores, etc. This second form of moisture changes electrical properties, causes the formation of electrolytes that secondarily corrode materials, or causes decomposition when frozen by increasing its volume. This type is trapped on objects at low humidity, even below 40%, it is only a very thin layer, and is caused by micro-roughness. This condensation in a larger form can occur even though the relative humidity of the air is low, but the object has cooled down so that the air in contact with it has cooled down enough to reach saturation and condense on the object. Relative humidity also varies greatly with height above the ground, which should be taken into account when storing equipment (Sarabia-Riquelme *et al*., 2023).

1.1.3 Impact of chemical air pollution

Chemical pollution of a certain area, as it is caused by industrial plants at a certain location. The most common atmospheric pollutants in the air are: sulfur dioxide, carbon dust, nitrogen, hydrogen sulfide, and others. All of them accelerate the destruction of materials. In coastal areas, significant destruction is caused by the presence of salt in the air (Patel *et al*., 2014).

1.1.4 Impact of microorganisms

Microbiological destruction is caused by fungi and bacteria. Their reproduction is favored by high humidity, temperatures above 2ºC, and light. Microorganisms either feed on organic matter or decompose it, and the products of their metabolism destroy or pollute materials. The best protection is the correct selection of materials, and if some materials are unavoidable, they must be impregnated with fungicides and insecticides. It is useful to fight microorganisms by eliminating the conditions that favor their development, which are temperature, humidity, and light (Birgander *et al*., 2018).

2. Main Body

2.1. Maintenance of the hull

The hull of a ship is the main load-bearing structural element of a ship, therefore special attention is paid to its maintenance. The scope of maintenance primarily depends on the type and age of the ship and the level of maintenance in the previous period. The condition of the ship's hull is determined by assessments by the ship's command and inspectors, and by inspections by authorized organizations. Based on the determined condition, the shipping company receives guidelines for the necessary maintenance in the future. The level of maintenance has an impact on the capital value of the ship, which is primarily reflected when selling on the used ship market. In most cases, additional investments in maintenance contribute to achieving a higher price for the ship (Strandenes, 2013).

Hull insurance premiums are based on the market value of the ship. However, the amount of premiums is also affected by the amount of claims for damage in the past period. Higher amounts of claims for damage result in an increase in the premium amount in the following period. Poorly maintained ships are certainly not attractive to a better-quality crew.

Therefore, it can be expected that such ships have a less-quality crew that is changed more often. In such cases, even additional financial investments in maintenance do not achieve the desired effect (Hartanto, 2020).

According to experience, with appropriate protection with coatings and cathodic protection of the hull, a ship can be economically exploited for over twenty-five years without replacing the sheets and structural elements. The first coatings are applied during the construction of the ship and are occasionally partially or completely renewed during economic exploitation. In the event of failure to renew the coatings, corrosion occurs, the effects of which become more obvious as the ship ages. Usually, in the time between the second and third renewals of a ship's class, major changes in sheets and structural elements occur, most of which are damaged by corrosion (Wei *et al*., 2018).

The direct expenses of maintenance costs are increasing, as are the indirect costs caused by the ship being stopped. Actually, an inhibitor is any substance that, when added to an environment, reduces the corrosion of metals. Maintenance methods and investments usually depend on the planned time of economic exploitation of the ship. On the basis of the planned exploitation time, the shipping company decides on the most economical maintenance interventions in a certain period of time. Experience has shown that surface preparation and application of new coatings on damaged parts of the old coating is economically justified in cases of planned exploitation of the ship in the next five to eight years (Koch *et al*., 2016). When the ship intends to remain in operation for less than five years, lower quality so-called «soft»2 coatings or cathodic protection.

The most common cause of damage to a ship's hull and its structural elements is corrosion (Xu *et al*., 2021). Nowadays, marine steel and aluminum are commonly used in the construction of the ship's hull. In principle, corrosion can be prevented or reduced in four methods by:

- Material selection,
- Environmental modification,
- Protective coatings or coatings,
- Cathodic and anodic protection.

The properties of shipbuilding steel depend on the proportion of impurities that affect its chemical and mechanical properties. The most important element is carbon, which is up to 15%. It is divided into grades A, B, D, and E based on its chemical composition and physical properties. Quality determines the price, which gives the shipping company the opportunity to choose the quality, but only within the required limits set by the classification societies. Aluminum, due to its specific weight, is used today in the construction of very fast vessels (Rodrigue, 2017).

The oxide layer that appears on the surface of the metal protects very well from corrosion. However, its damage leads to an accelerated corrosion process. Galvanic corrosion occurs in aluminum and its alloys. By environmental modification we mean the change of electrochemical composition by the use of inhibitors. The mechanism of corrosion reduction is based on the reduction of the total energy involved in a corrosion process. There are cathodic and anodic inhibitors.

Cathodic inhibitors increase the polarization of the cathode, and anodic inhibitors increase the polarization of the anode. Soluble hydroxides, chromates, phosphates, silicates and carbonates are used as anodic inhibitors. Cathodic inhibitors are zinc, magnesium and nickel salts. They are mostly used on board in systems with a circular flow of water. The application of protective coatings is probably one of the oldest methods of corrosion protection. The characteristics of this method are simplicity and speed of application and relatively low cost. They can be applied by the ship's crew without special training. Damage and insufficient protection are easily noticeable and can be easily repaired (Sastri, 1998).

Cathodic protection is commonly used to protect the ship's hull. Cathodic protection can be performed using sacrificial anodes or forced current, which is analyzed and discussed below. Theoretically, each of these last two methods can be applied independently and in combination with coatings. However, the combined application of these methods provides more effective protection. Damage often occurs during the economic use of the ship coating, so that part of the ship's hull remains unprotected. In order to comply with the protection requirement of the ship's hull, there is a need to apply electrochemical protection on the part with a damaged coating. It is also possible to apply electrochemical protection on the ship's hull without protective coatings, however, it is very difficult to achieve an even distribution of the protective current (Kramar *et al.,* 2021).

Protective coatings complement protection and reduce electricity consumption. Therefore, the ship's hull is usually protected with coatings whose quality depends on the price, and cathodic protection is used as an additional protection system.

2.2. Properties of organic coatings

Each anti-corrosion coating has a greater or lesser permeability to water. A protective layer that absorbs water tends to swell, which leads to a weakening of the adhesion of the coating to the metal substrate. The impermeability of the layer prevents the penetration of water and ions to the metal substrate. Water absorption is affected by the density of crosslinking of polymer components in the layer, the presence of water-soluble components, the thickness of the protective layer, salinity, sea temperature and sea current speed. The following conditions are set for long-term anti-corrosion protection (Zhou *et al*., 2023):

- High mechanical resistance,
- Resistance to peeling,
- Chemical stability,
- Stability when applying electrochemical processes.

All conditions except the last one apply to all types of coatings applied to metal surfaces. Stability when applying electrochemical processes depends on the permeability of the coating to corrosive substances and the existence of mechanical damage to the coating and the bare metal surface on which electrochemical corrosion reactions can take place. The electrical voltage that causes the movement of ions ranges from a few tenths of a volt to several volts. The cause of ion movement is anodic and cathodic polarization. Anodic polarization occurs at the point of the outgoing current, i.e. at the junction with the foreign cathode. Cathodic polarization occurs at the point of stray current entry. Electric bubbling of the coating occurs as a result of ion movement. During anodic polarization, corrosion damage occurs at the point of separation. With cathodic polarization, there are no changes on the metal surface except slight traces of corrosion (Silverman, 1998).

Coatings can be applied with or without air. The coating can be at a higher or lower temperature during application. Airless spraying is usually used for applying thicker anti-corrosion coatings. The coating application pressure is approximately 0.1 MPa, which allows for better adhesion.

In addition to the methods described, it is also possible to use the electrostatic spraying technique. The metal surface is electrically charged with an opposite charge to that of the coating being applied (Fauchais and Vardelle, 2012).

Chlorinated rubber is a one-component resin that is widely used in anti-corrosion protection in conditions where high resistance to water and acids is required. Unlike natural rubber, chlorinated rubber is brittle and is used in combination with various plasticizers. The preparation of the substrate for coating application must be satisfactory. It shows good resistance to atmospheric conditions (Sakhri *et al*., 2010). The required drying time for a coating with a thickness of 30 – 40 µm is approximately 6 hours, while a coating with a thickness of 60 – 80 µm dries in 12 hours. Mutual adhesion of multiple layers is good, provided that satisfactory cleanliness is ensured before application.

2.3. Surface preparation

Surface preparation and cleaning can be carried out at surface temperatures of at least 3 ºC above the dew point or if the relative humidity is below 90%, unless otherwise recommended by the coating manufacturer. The metal surface should be properly prepared before coating. Before coating, it is necessary to remove the oxide film (scale), corrosion products, and all other impurities on the metal surface (Standard, 2012). Common methods of preparing metal hull surfaces before coating include:

- Degreasing,
- Removal of the oxide film (scale) by exposure to atmospheric influences,
- Mechanical removal of corrosion products,
- Removal of corrosion products with abrasives and water,
- Removal of corrosion products by fire,
- Chemical cleaning and removal of corrosion products.

Degreasing involves removing grease and oil from metal surfaces. Since physical removal alone is not thorough enough, cleaning is carried out using organic solvents or detergents dissolved in water. Thorough removal of oil and grease is necessary because even small amounts cause anomalies on the surface. This creates a predisposition for pitting corrosion. Also, the protective coating does not adhere to the surface and it is quickly damaged and exposed to corrosion.

2.4. Coating application conditions

In addition to a properly prepared surface, the prerequisites for a good and durable coating are the appropriate conditions under which the coatings are applied. The properties of the coating are significantly affected by atmospheric humidity and temperature during application and immediately after the method is completed.

Applying a coating during high air humidity can cause damage to standard coatings. Moisture condenses on the metal surface, enters its pores, causing corrosion and reducing the adhesion of the coating to the metal. The coating applied to such metal changes its composition, causing bubbles and cracking of the coating. The moisture content in the air is usually expressed in relative humidity. When the relative humidity is high, a small drop in air temperature can cause condensation. Such conditions are especially pronounced during weather changes. In order to most successfully apply coating protection, it is necessary to select the most suitable meteorological conditions. Considering the air humidity, the limitations of coating application are as follows (Bortak, 2002):

- Coating application is not performed if the relative humidity is over 85%, except for coatings that are intended for application in such conditions;
- Surface temperature must be at least 2 to 3 ºC higher than the dew point temperature;
- Coating application cannot be carried out outdoors during rain, snow, fog, increased concentrations of pollution in the air.

The application of epoxy coatings at temperatures lower than 10 ºC is not recommended, and polyurethane resins at temperatures below 5 ºC. At low temperatures, the viscosity of the coating decreases and they are very difficult to apply. The situation can be improved by using thinners recommended by the coating manufacturer. When the temperature drops below 1 ºC, any coating application should be postponed due to the presence of ice in the pores of the metal. Such conditions prevent the adhesion of the coating to the metal and reduce the anti-corrosion protection of the coating. At temperatures higher than 30º C, there is a possibility of porous, uneven coatings being created on a rough surface.

It is very important that the applied coating is of the required thickness. The achieved thickness depends on the method of application. Under controlled application conditions, the achieved thickness is satisfactory on approximately 90% of the surface. On approximately 10% of the surface where a satisfactory thickness is not achieved, the coating is applied at least to the required thickness.

In Croatian repair shipyards, quartz sand is most often used as an abrasive in the sandblasting process. Sandblasting is performed by treating the metal surface with compressed air mixed with sand. The sand grains hit the metal surface at high speed, removing corrosion products, scale and old coating deposits. A rougher surface is achieved, enabling better adhesion of the coating that is applied later.

The method of removing corrosion products and cleaning metal surfaces using a combination of water and abrasives is increasingly being used. This method avoids the harmful effects of dust on human health, reduces abrasive consumption and removes water-soluble impurities. It is recommended to add inhibitors compatible with the primer to the water in order to prevent corrosion. The method impurities with water involves the use of water under high pressure between 15 and 30 hPa. This method has recently begun to be used more intensively in the treatment of the outer shell of a ship and deck. It enables the removal of corrosion products, accumulations of marine organisms on the underwater part of the hull, and salt.

Using special equipment, a water pressure of 300 MPa is achieved, thus removing larger deposits of corrosion products and coatings. By regulating the water pressure, it is possible to remove the top layer of coating without damaging the bottom coating. Thermoplastic coatings can only be removed using this method. The combination of water, abrasive and air provides the most effective method of surface preparation. The metal surface is very well cleaned of corrosion products, salt and all other water-soluble impurities on the metal are removed. Inhibitors are usually added to the water. This method also significantly reduces environmental pollution and the possibility of harmful consequences for human health compared to sandblasting. Also, using this method, special abrasives are not used. The main disadvantage is the inability to apply the coating immediately after the end of the application of this method due to the humidity of the surfaces (Liu *et al*., 2018).

The corrosion product is easily removed from the metal surface by hammer blows. The method is suitable for removing old coatings and coatings. The coating that burns off during this process has a harmful effect on human health and the environment. Chemical cleaning and removal of corrosion products has limited application in ship hull protection. It is usually used after corrosion products have been removed mechanically (Guo *et al*., 2019). It is also used to remove thinner deposits of uniform surface corrosion when mechanical removal is ineffective. On passenger ships during regular operation, it is used to clean coatings from traces of corrosion products.

2.5. Protection of ship hull with coatings

Protective coatings can be metallic and non-metallic. Metallic coatings can act as anodes. Acting as anodes, they protect the metal surface cathodically. In cases where the coating has higher corrosion resistance, it acts as a barrier between the metal surface and the electrolyte.

Non-metallic coatings can be inorganic and organic. Inorganic coatings include oxides and poorly soluble layers of chromates and phosphates. Organic coatings and coatings are most widely used in corrosion protection. Organic coatings and coatings are therefore also used in corrosion protection of the internal and external surfaces of ship hulls (Harsimran *et al*., 2021). The quality of protection of the applied coating on the ship hull depends mainly on the following factors:

- Coating properties,
- Chemical properties of the metal surface,
- Preparation of the metal surface,
- Coating application technique,
- Thickness of the applied coating,
- Quality of application,
- Climatic conditions during surface preparation, during coating application and after coating application,
- Aggressiveness of the environment during coating application and during economic exploitation of the ship.

The protective coating system used for hull protection typically consists of a primer, an intermediate layer and a top coat. Each of these layers has certain properties that contribute to the compactness and durability of the protective coating. The primer is the first layer applied to a cleaned and prepared surface (Suárez-Vega *et al*., 2024). Its quality is measured by the following properties:

- Preventing or delaying the occurrence of corrosion,
- Forming a solid layer that adheres well to the metal surface,
- Repairing chemically active surfaces,
- Elasticity during temperature changes

The intermediate layer usually complements the anti-corrosion protection of the primer, and should be a good base for the final layer. Its characteristics must match the primer and final layers.

The basic property of the final layer is to provide protection against weather and chemical influences. The final layer can be a convertible or non-convertible coating. Convertible coatings are materials in which the drying process occurs together with oxidation and polymerization, such as epoxy and polyurethane resins. Non-convertible coatings are materials in which the solvent evaporates during drying, and the resulting layer does not change significantly under the influence of the atmosphere. This group includes, for example, vinyl copolymers and rubber derivatives.

Today, two-component epoxy coatings consisting of resin and hardener are also used in ship hull protection. Typically, all organic coatings consist of pigments that make the coating opaque by giving it the desired color, plasticizers that shape mechanical and binding properties, and solvents that control viscosity and drying speed (Ranjbar *et al.*, 2009).

The basic function of all protective coatings is to create a barrier between the environment and the metal surface being protected. However, it should be emphasized that protective layers are to some extent permeable to water or water vapor, so that the metal surface is not completely isolated from the environment. Protective coatings create an anti-corrosion effect through the following properties:

- The coating, with its high electrical resistance, creates polarization of corrosion reactions;
- They prevent oxygen from reaching the metal substrate, thus slowing down the cathodic reaction,
- Slowing down the anodic reaction by concentration polarization.

Different types of pigments with specific effects can be added to the base coating. Inert pigments such as aluminum, stainless steel and chalk particles enhance the insulating effect of the basic polymer film by closing micro-paths within the protective layer. Metallic pigments such as zinc powder slow down corrosion by acting as cathodic protection, and zinc particles act as anodes.

2.6. Classification of organic coatings

Organic protective coatings are usually divided according to the plasticizers that determine the basic mechanical and binding properties, water resistance, chemical composition and origin. Epoxy coatings have a very wide application in ship hull protection. They form the basis for various anti-corrosion coatings and coatings. They can be applied at room or elevated temperatures. They can be used with or without solvents. They can be one-component and two-component. They are obtained by combining three types of organic resins:

- Melamine, urea and phenolic resins,
- A combination of fatty acid esters,
- A combination of epoxy coatings and various hardeners.

One-component coatings can be obtained from epoxy-ester resins. Epoxy resins have high hardness, abrasion resistance and good adhesion to the surface. Two-component coatings use certain types of hardeners to improve the properties of the coating. Hardeners based on polyamines, amines, and polyamides are most often used. Epoxy coating with polyamine as a hardener is highly resistant to the influence of chemicals and solvents. Coatings are prone to chalking, are brittle and resistant to erosion when exposed to the atmosphere.

Tar epoxy coatings are widely used in ship hull protection. Especially in areas where a highly corrosion-resistant coating is required. They have proven to be very successful in protecting ship ballast tanks and crude oil transport tanks. The coating has good water resistance. However, its resistance to solvents and acids is lower than that of conventional epoxy coatings. Tar epoxy coatings are used at lower ambient temperatures. The amount of solvent used depends on the thickness of the coating. Baked epoxy coatings with phenolic and amino resins as hardeners have the highest chemical resistance. Curing takes up to one hour at a temperature of approximately 200 ºC. The best chemical resistance is achieved with phenolic resins used as coatings on chemical transport tanks. Polyurethane resins are used in a variety of protective coatings (Ranjbar *et al.*, 2009). Anti-corrosion protective properties are similar to those of epoxy resins, and can be:

- One-component air-drying,
- One-component air-drying with moisture from the air as a hardener,
- One-component baking,
- Two-component with hydroxide as a hardener at room temperature,
- Two-component with a catalyst as a hardener.

Alkyd coatings usually contain fatty acids, the content and quantity of which determines elasticity, durability, drying time and other characteristics. Paint bases can be combined to obtain coatings with improved properties. For example, vinyl alkyd coatings dry quickly and have better resistance to water. Chlorinated rubber alkyd coatings are durable at high temperatures and in adverse weather conditions.

2.7. Ageing of corrosion coatings

Aging does not necessarily mean that the coating loses its protective properties, but corrosion of the metal beneath the coating often occurs. This is because organic coatings are always more or less permeable to water. Low-molecular compounds that oxidize easily, such as rosin, bitumen, oil oxidation products, and others, decompose quickly. Destruction products evaporate easily, are easily washed away, the intermolecular bonds of the coating weaken, which causes cracking of the coating, and if crosslinking has occurred in the coating, its elasticity and plasticity decrease, and even with small deformations it cracks. Peroxides are very harmful to coatings of organic origin. The rate of aging of the coating is inversely proportional to the degree of saturation of fatty acids. Structural changes that occur during aging of coatings made of polymers with a high molecular weight are related to chain relaxation. Relaxation is accelerated by increasing temperature, swelling, and humidity. If the relaxation processes are not completed by the formation of the coating, the coating subsequently cracks, as is the case with nitro varnishes (Fredj *et al.*, 2010).

The coating becomes cloudy when secondary structural compounds are formed, or when the solid solution turns into a colloidal multiphase system. The stability of the coating to chemical aging reactions in the atmosphere depends on the chemical system of the compounds, and can be divided as follows:

- The most stable are compounds that undergo crosslinking, while containing a minimum number of functional groups;

- Saturated chain polymers (polyvinyl chloride) and polymers that retain the largest number of their functional groups;
- Compounds that undergo crosslinking, while preserving a larger number of functional groups, such as coatings of excess vegetable oils;
- Chain polymers that contain a larger number of functional groups, such as rubber.

Compounds with a low molecular weight, such as bitumen and rosin are the least stable. The influence of coating aging on resistance to atmospheric agents. The most important factor is the duration during which a coating meets the corrosion protection requirements under operating conditions, mostly in atmospheric conditions.

A major role is played by the pre-treatment of the surface before applying the coating, the chemical stability and possible inhibitory effect of pigments, the adhesion power of the coating and the stability of the coating to the external environment. The most aggressive components are oxygen and water. Under their action, sunlight, light and heat accelerate the destructive effect several times. Coatings made of polymers with a high molecular weight are well maintained, but they do not protect the metal from corrosion due to poor adhesion, so corrosion occurs under the coating.

Bitumen coatings are naturally drying coatings based on asphalt, bitumen or coal. They can be used to protect against atmospheric corrosion as well as surfaces below the waterline. The coatings are diluted with solvents to reduce their density (Cole and Marney, 2012). The characteristics of bitumen coatings are as follows:

- Limited resistance to solar radiation,
- Drying period depending on the coating base and solvent; usually between 2 and 6 hours,
- Good ventilation is required for coatings applied indoors,
- Mutual adhesion of the coatings is good provided that salt and oil residues have been removed beforehand.

Epoxy and silicone-based primers are commonly used in new construction where the zinc dust content provides better protection. The main disadvantage of zinc dust primers is that exposure to atmospheric influences and chemicals causes the release of zinc salts, preventing good adhesion of the next coat of paint. Therefore, before applying the next coat of paint, the surface must be properly cleaned with brushes. The application of the latest self-polishing coatings has not completely solved the problem of anti-fouling protection due to certain disadvantages such as:

- The coatings are very expensive,
- They require good surface preparation during application,
- It is necessary to ensure suitable atmospheric conditions during application,

- They are sensitive to mechanical damage.

2.8. Protection of tanks and stones

Ships sailing without cargo usually load ballast tanks. The loaded liquid becomes an electrolyte, which causes corrosive processes to occur. Ballast, fuel, waste water and stone tanks are protected by galvanic anodes and protective coatings. The surge current protection system is not used primarily for safety reasons.

2.8.1 Tank protection

The application of cathodic protection in tanks is defined by the rules of classification societies. It is recommended to coat the upper part of the tanks, up to approximately 1.5 m below the cover, with a dedicated protective coating. The lower part, which reaches approximately one meter above the bottom of the tank, is usually protected with protective coatings and sacrificial anodes. When protecting the middle part of ballast tanks, there is the possibility of protection with coatings or a combination of coatings and sacrificial anodes in such a way that the horizontal surfaces are protected with coatings and the other surfaces with anodes. In tanks intended for the transport of crude oil, the horizontal surfaces of the middle part of the tank are usually protected with protective coatings. The protection area also includes various pipelines located in the tank and the supports.

2.8.2 Protection of Stones

Stones cannot be protected by the usual method of sacrificial anodes used to protect hulls and tanks. The dirty water that collects in them is not sufficiently active. In order to ensure adequate protection, anodes are made of aluminum or zinc wire. The thickness of the wire is usually 6 to 10 millimeters. The wire is placed along the structural removing corrosion products with abrasives and water is one of the most efficient methods and provides an optimally prepared surface for the application of protective coatings. Ship hulls are most effectively treated with this method. It is especially used during the ship's stay in the repair shipyard, and very rarely are the decks and warehouses treated with this method during the economic exploitation of the ship. The most important conditions that must be met for effective removal by abrasives are:

- Selection of the appropriate abrasive,
- Periodic removal of dust and dirt,
- Appropriate pressure under which the abrasive acts,
- Presence of dry air (when required),
- Suitable ratio of air, water and abrasive in the method where this combination is applied.

Brushing is necessary to remove small residues of corrosion products. Chemical surface treatment with appropriate corrosive agents based on sulfuric or hydrochloric acid is preferred. Electrical and pneumatic tools achieve significantly better surface treatment. The most commonly used abrasives are sand and shot, and a combination of abrasive and water. Therefore, the removal of corrosion products can be divided according to the type of abrasive into:

- Sandblasting,
- Shot blasting,
- Combination of sandblasting or shot blasting with water,
- Removal of corrosion products and impurities with water.

2.9. Water-based coatings

International and national regulations are increasingly directing coating manufacturers to research and offer coatings that are less aggressive to human health and the environment. Coatings that are currently in the technological development phase and are considered environmentally acceptable are:

- Coatings with a high solids content,
- Powder coatings,
- Radiation-curing coatings,
- Water-soluble and water-dilutable coatings.

Water-dilutable coatings began to appear on the market in the middle of the last century.

Over the past ten years, there has been a significant technological improvement in coatings.

The composition of the coating is prepared with regard to the intended purpose of the coating. In general, water-based coatings can be divided into three main groups:

- Aqueous solutions,
- Aqueous dispersions,
- Aqueous emulsions

In water-soluble paints, the molecules of the water-soluble binder are completely dissolved in water. Organic solvents are mainly alcohols, glycol ethers and other oxygen-containing solvents that are soluble or miscible with water. Water-soluble paints have a relatively low dry matter content. Aqueous dispersions or colloidal coatings are water-dilutable systems made of dispersions of polymer particles in water. The particles are high molecular weight polymers (styrene, butadiene, acrylate). The dispersions contain a small amount of solvents, which serve as film formers, and which partially evaporate upon drying. Emulsions or latex paints are similar to aqueous dispersions. An emulsifier is needed to keep the clumps in suspension. In their composition, emulsions contain various binders.

2.9.1 Protection of the underwater hull from fouling

The underwater part of a ship in a marine environment is exposed to the possibility of fouling by marine organisms. Fouling causes a gradual increase in the roughness of the outer underwater part of the ship's shell, which results in an increase in resistance during navigation. An increase in hull resistance may require approximately a 10 to 15% increase in thrust to maintain the same speed, which clearly causes, among other things, higher fuel consumption and therefore higher ship costs. Fouling is more intense if the ship is moored in a port or at anchor near the coast. Areas of the ship's hull are usually not uniformly fouled due to the water flow itself and the way organisms attach to each other. The acceptance of organisms on the ship's shell varies from a few hours to a few days. Some marine organisms can attach to each other at ship speeds exceeding 4 knots.

The first written evidence of treating the bottom of a ship dates back to the 5th century BC. Research shows that the ancient Phoenicians and Carthaginians used tar, arsenic and sulphur mixed with oil, while the Greeks used tar or wax, and lead plating. To protect the underwater part of the ship, the English in the 15th century used lead, which has poorer antifouling properties, but proved to be good at protecting against wormholes. Copper plating was used for protection against fouling from the 17th to 19th centuries, when with the advent of iron ships, such protection was completely abandoned. The first iron ship was the barge Trial, launched in Coalbrookdale, England, while the first iron ship Aaron Manby was built in 1822 in Tipton, near Coalbrookdale. It sailed between Paris and Rouen. With the advent of steel hulls, the problems of steel melting in contact with copper plates and fouling arose. The English scientist Davy, at the request of the British Admiralty, studying this phenomenon in 1824, announced that a galvanic cell forms between two metals in a salt solution, in the presence of oxygen, and thus causes gradual corrosion of one of the metals. Based on his research, he suggested that small amounts of zinc or wrought iron be placed in contact with copper to prevent corrosion of the iron. The safest protection against corrosion and fouling of steel ships consisted of a well-insulated wooden (teak) lining as a barrier between the steel substrate and the copper plates. The effect of the teak lining was twofold:

- The formation of a galvanic cell between iron and copper was prevented
- Fouling was reduced because copper gradually dissolved in contact with the sea, thus acting as a toxin on fouling organisms.

However, it was not until the mid-19th century that the problem of galvanic corrosion of steel hulls and the need to protect the hull with coatings that would not produce a negative impact were seriously considered, and the application of coatings that basically worked by releasing toxic substances began. The most commonly used toxic substances were copper, arsenic and mercury together with their compounds, and turpentine, petroleum and benzene were used as solvents. Such antifouling agents were relatively expensive and often short-lived. In the first half of the 20th century, Italian Moravia (a coating based on hot plastic, a mixture of natural resin and copper compounds) was used as an antifouling agent.

2.10. Modern protective coatings

The first written patent for a solution for protecting a wooden ship dates back to 1635, by the English goldsmith W. Beale, who only states that the base for the coating mixture is minerals, while other details are unknown. The first to practically approach the problem, the chemist W.J. Hay, proposed two layers of coating mass for protecting an iron hull:

- The first layer to prevent corrosion,
- The second layer to prevent fouling.

Until the second half of the 19th century. a number of anti-fouling patents have already been registered, however, the most attention is the invention of Captain John Rahtjen, who in 1860 patented two coating compositions in Bremershaven. It is precisely these coatings that are considered a forerunner in technology production of ship coatings. Instead of tar, Rahtjen uses shellac as a base medium. The first layer of underwater ship plating is covered with minimium, while the second layer of coating contains mercuric oxide and arsenic. Its composites not only effectively prevented fouling, but also dried quickly. In the first decade of the 20th century, approximately 85% of the British fleet was protected by Rahtjen coatings.

Due to the need for docking, cleaning and coating of the underwater part of the hull, ships until the beginning of the 20th century. dock for very short periods of time (two to three months). Until the middle of the 20th century, the effective life of antifouling coatings was only 9-12 months. After entering the marine environment, the component has a harmful effect on its flora and fauna, causing mutations in certain organisms. The main types of antifouling coatings are:

- Conventional matrix coatings,
- Improved matrix coatings,
- Self-polishing coatings.

Conventional matrix coatings appeared during the 1930s. They were active for between 12 and 15 months. The reason for the short period of activity of the coating was limited mechanical strength. During the life of the coating, there is a constant release of bioactive substances that dissolve in the sea. It was recommended to apply the coating while the ship was docked, and after the coating had dried, it was necessary to lower the ship into the water due to the possibility of the coating cracking.

The improved mechanical properties of the coating allowed the use of thicker coatings. Also improved performance of bioactive substances extended the active life of the coating to 18 to 30 months. Bioactive substances did not dissolve in water but were released from the coating and reached the environment. The coating remained porous, without bioactive action, which at the same time increased the friction of the ship's hull.

Unlike other coatings of this type, they represent a physical and chemical combination of an anti-corrosive and biocidal coating. The main component is an organic copolymer with very good mechanical strength that allows the application of thicker coatings. The period of time between two dockings of the ship could be increased to 5 years. The organic component chemically acts on the acrylic element in the organic copolymer, which is released in contact with seawater. The rest of the coating dissolves in seawater and is released from the surface due to the movement of the ship. Typically, a layer of coating between 73 and 100 µm is released during the year. The continuous release of bioactive substances and the release of the rest of the coating during navigation ensured a constant smoothness of the surface.

Modern anti-fouling coatings for underwater hulls the effectiveness of coatings that prevent fouling of the underwater hull is reflected in their prevention of organisms from adhering to the hull's coated surface. However, regardless of the durability of the coating, the ship must be docked for the prescribed periodic inspections of the hull and its accessories on dry land. Selecting a specific anti-fouling coating is not easy and therefore the ship-owner, considering the technical, technological and commercial requirements placed on a particular ship, makes the selection based on the following basic factors:

- The purpose of the ship,
- The ratio of sailing and stationary time (staying in port and anchorages),
- The navigation area,
- The speed of the ship,
- The period between two dockings,
- Compatibility with the anti-corrosion coating,
- The degree of smoothness of the coating.

Antifouling coatings are divided according to the basic mechanism of their toxicity:

- A coating that releases a toxin in contact with the sea,
- A coating in which the binder affects the toxicity due to its solubility,
- A coating in which the binder itself is toxic,
- A coating with combined action.

Antifouling coatings are divided according to the chronology of their appearance on the market into:

- Conventional,
- Self-polishing with organotin compounds,
- New conventional,
- Self-polishing without organotin compounds,
- Hybrid: SPC without tin compounds / CDP conventional.

2.11. Conventional coatings

Conventional antifouling coatings were not durable and peeled off quickly. The physical and chemical properties of the coating film had to provide toughness, durability and good adhesion to the substrate at the same time (a coating with too high a proportion of toxins weakened the physical properties of the film). Such coatings contain biocides, which in most cases belong to the group of heavy metals. Arsenic, which was often used in such coatings at the beginning, remained until the 20th century in combination with mercury compounds in coatings where the main biocide was copper oxide. The biocide in such coatings is finely dispersed, and its excretion occurs in direct contact with the sea. Copper oxide is the basic biocide in almost all conventional coatings. The biocidal effect is determined by the rate of excretion of the biocide, and is expressed as the amount excreted from a unit of substrate surface over a certain time.

In addition to the solvent white spirit, the first conventional coatings (Old-Type, Traditional) contained either a large proportion of resin from various trees with relatively small proportions of bioactive material (20-25% copper oxide), or a small proportion of binder with large proportions of bioactive material. The disadvantage of conventional coatings was that the rate of biocide release was disproportionate to the adhesion of vegetation to the substrate. Increasing the speed of the ship increases the rate of biocide release, and at approximately a speed of 8-10 knots, the adhesion of organisms stops. The most intensive adhesion of vegetation occurs when the ship is stationary, because then the biocide release is the lowest. The use of natural resin from tree bark (rosin) in the coating binder system modifies the anti-fouling coating in such a way that it enables the simultaneous dissolution of both toxins and binder, which results in the thinning of the coating film layer over time. Vessels protected with conventional rosin-based antifouling coatings had to be launched into the sea immediately after application.

Rosin has a fragile structure, so despite the addition of various softening substances, it did not allow increasing the thickness of the coating. The first conventional antifouling coatings had a relatively short shelf life. In anaerobic conditions, the harbor is home to active bacteria that reduce sulfates from the sea to sulfides that can react with the copper oxide of the coating, converting it into insoluble copper sulfide (the biocidal effect is stopped, allowing fouling). The accumulation of coating after coating, after a series of dockings, and mechanical damage over the years, caused delamination and peeling of old coatings.

The construction of specialized ships with large carrying capacities in the middle of the last century also required new approaches to the application and action of antifouling coatings. Within the group of conventional antifouling coatings, a group of coatings commercially called long-term antifouling coatings appeared. Such coatings appear under various names, but they have in common that insoluble binders, vinyls, epoxies or chlorine rubber, are added to the coating system of conventional antifouling coatings to strengthen the film.

The basis of action: the soluble resin from the coating is excreted together with the toxin, and the insoluble resin (binder) remains on the surface. In addition to copper oxide and organotin compounds, other biocides were used, such as mercury and arsenic, but they were quickly abandoned due to their high toxicity. In the deeper layers of the coating, the biocide remained unconsumed because it could not be excreted to the surface. Activation of the biocide in the deeper layers could only be achieved by sanding the worn layers of paint. Improved antifouling coatings usually lasted up to two years. The generation of the coating caused it to peel and fall off. Applying a new layer of coating required the application of a leveling layer. Conventional antifouling coatings also include so-called reactive coatings. In these coatings, a porous layer also appears after the biocide wears off, which is most often removed with special brushes, leaving a fresh layer of coating. Underwater sanding with rotating brushes was usually performed. The disadvantage of such cleaning is that the coating layer is not removed evenly (Arai *et al.*, 2009).

Self-polishing antifouling coatings with organotin compounds. In the early 1970s, the sudden increase in fuel prices required a change in the very concept of ship maintenance. Better business efficiency led to a reduction in the number of interventions on the maintenance of the underwater part of the ship's hull.

The discovery of the strong biocidal effect of tributyltin compound (TBT) on marine flora and fauna leads to further evaluation of antifouling coatings. The first application of TBT in antifouling coatings did not give satisfactory results because the liquid biocide was excreted too quickly from the applied coating. In the early 1970s, it was possible to obtain a controlled rate of excretion of TBT biocide by a certain polymerization process.

Organotin biocides chemically bound to the copolymer were released from the binder upon contact with water by the process of hydrolysis and/or ion exchange. The rest of the coating (polymer chain) dissolved in water. In this way, it enabled the new coating surface to actively act in its environment. Linear biocide release was achieved, and the antifouling coating was active until the last coat was worn out. The specificity of these coatings was in the controlled release of the tri-butyltin compound from the copolymer binder, and the parallel smoothing of the coating.

The durability of such coatings was required to be in line with the prescribed docking of the ship by classification societies. In addition, the coatings had to meet the specifics of the ship's navigation areas, the ship's speed, as well as satisfactory smoothness of the hull's coated surface in all phases of coating wear. The use of self-polishing coatings with tributyltin compounds in a very short period of time displaced conventional anti-fouling coatings from use (Ivče *et al*., 2018). Primarily due to economic indicators that appear as the following factors:

- The achieved hull smoothness resulted in lower resistance and a decrease in fuel consumption
- The period between two dockings increased to five years.
- The cost of preparing the surface for coating application was reduced.

Already in the late 80s, the harmfulness of organotin compounds for marine flora and fauna was recognized. However, it was only from January 1, 2003 that the use of organotin compounds was banned, and ships were required to have a special certificate stating that the coating applied to the underwater part of the hull was TBT-free.

2.12. Self-polishing AV coatings without organotin compounds (SPC TBT-free)

Reintroducing copper biocide instead of tin did not yield satisfactory results. Further research was focused on finding a technology that would evenly release the biocide by self-polishing as in TBT antifouling coatings. In the early 1990s, new products based on a copolymer binder containing copper and zinc acrylates were put on the market. Lower biocidal activity of copper and zinc copolymers, compared to the classic TBT coating, was achieved by using a biocide enhancer (the most commonly used compound is zinc pyrithione, which is not permanent and does not accumulate in marine flora and fauna). The action of hydrated sodium chloride molecules from the sea releases copper ions from the copolymer binder by hydrolysis, which causes an ion exchange reaction and the copper ion binds to the chloride ion from sodium chloride, while the sodium ion binds to the hydroxyl group of the acrylic copolymer. This reaction enhances the solubility of the coating binder and is gradually washed away, thus self-polishing the coating. The self-polishing effect corresponds to the self-polishing process for classic TBT coatings (Terlizzi *et al.*, 2001). The dissolution reaction takes place only on the surface layer of the coating in contact with the sea, while the rest of the coating, with its hydrophobic nature prevents the penetration of the sea. In this way, it is possible to control the release of biocides, so that the secreted layer of anti-fouling coating is always thin (<30 μm). The new TBT Free AV coating based on copper acrylate ensures the good properties that classic TBT coatings have:

- Lower fuel consumption,
- Satisfactory fouling control,
- Control of biocide release,
- Control of polishing speed,
- Self-smoothing properties.

2.13. Two-component AV coatings

Coatings of this type consist of; CDP conventional coating and SPC TBT free coating. These coatings have slightly weaker characteristics than AV SPC coatings (without tin). The synergistic action of the hydrolyzing binder technology (based on copper acrylate) and the binder based on resin acids (rosin, CDP technology) provides satisfactory efficiency. The CDP component provides the coating with good surface properties and a high solids content. The SPC TBT component controls the polishing speed and release of biocides, and the reduced thickness of the secreted layer.

2.14. AV coatings without biocides, anti-fouling coatings

Coatings without biocides, which also prevent the attachment of living marine organisms due to their perfectly smooth surface, represent an ideal coating without harmful effects on marine bioworld. Such coatings are usually based on silicone or Teflon polymers that create a surface with an ideal degree of smoothness that prevents organisms from attaching. However, in stationary conditions, despite the slippery surface of the coating, it is not possible to avoid partial fouling.

2.15. Silicone coatings

At the end of the 20th century, the possibility of using anti-fouling coatings for ship hulls that would prevent the adhesion of organisms began to be considered. Such coatings were supposed to be primarily non-toxic. After many years of research, it was possible to produce a polymer-based coating composed of polydimethylsiloxane molecules. Coatings based on PDMS polymers are very smooth, with a different surface texture than that of TBT-free SPC coatings. The coatings under consideration have not yet found wider application, primarily due to their price. However, it should be noted that silicone coatings cannot demonstrate their optimal properties at lower speeds and unfavorable sailing-stationary conditions, which is still evident in the tanker and bulk carrier fleets that make up the largest share of the total world fleet.

2.16. Microfiber-based coatings

After ten years of research, the company Seal Coat introduces new microfiber-based materials to AV coatings, called Seal Coat AV. The coating is applied by first applying a layer of adhesive to the surface, onto which millions of microfibers are sprayed. Each microfiber is electrostatically charged and placed vertically on the adhesive coating, creating a silky surface. The surface with microfibers placed in this way prevents fouling by bio-organisms. Microfibers are made of extremely tough synthetic materials that can last over five years on moving (floating) objects, and twice as long on stationary ones. The declared duration of this anti-corrosion-antifouling combination is up to five years. The coating is applied using traditional airless spraying equipment.

Unlike all previous anti-fouling protection systems, where it was important to know the gauze strip, this is not important here. Although this type of antifouling protection is still in the research phase, it is expected that future AV protection will be based exclusively on such coatings.

2.17. Efficiency of cathodic protection of the hull

Cathodic protection of the outer plating of the underwater part of the ship's hull is carried out for the purpose of corrosion protection. Corrosion protection has, among others, three clearly defined effects that can be economically measured during the operation of the ship, namely:

- Prevention of a decrease in the thickness of installed steel elements,
- Prevention of the occurrence of pitting corrosion,
- Maintenance of the smoothness of the ship's hull.

The action of corrosion leads to the dissolution of metal in the electrolyte. This type of corrosion is characteristic of chemically and physically inhomogeneous surfaces. The walls of the ship and other structural elements lose their thickness over time, and therefore their strength.

Pitting corrosion occurs on chemically and physically inhomogeneous surfaces. The metal, in this case ship steel, is not composed of homogeneous crystals. It is exposed to different oxygen concentrations, temperature and hydrodynamic properties of the electrolyte. Local cells are formed and the less noble metal dissolves due to the presence of the more noble metal.

In addition to the shape of the underwater part, the movement of a ship is also affected by the roughness of the ship's shell surface. The smooth surface of the ship's shell obtained with high-quality coatings can be maintained during exploitation by appropriate cathodic protection. Appropriate cathodic protection also extends the life of protective coatings. Appropriate cathodic protection can extend the durability of high-quality protective coatings by twenty years. Damage that occurs during regular exploitation is corrected during the ship's docking. The total protective current depends on the condition of the protective coating and the speed of the ship's movement.

Damage to protective coatings occurs when the ship rests on insufficiently protected banks during mooring or unmooring maneuvers and during the ship's stay at the mooring location, which results in the formation of bare metal surfaces. This fact causes the need to increase the value of the protective current. During economic exploitation, ships, unlike other objects, are in different corrosion conditions. On their shipping routes, they can sail in seas with different salinities and temperatures. The quantities of different dissolved salts and conductivity are the most important for the corrosivity and functionality of the cathodic protection system.

Cathodic protection is also a supplement to coating protection. The entire hull or only some of its parts can be protected. Usually, partial protection protects the stern of the ship, and in some cases the bow. The stern is subject to increased corrosion due to increased water flow. Another very important reason is the presence of attachments on the hull, such as the propeller and rudder. Partial protection of the bow is carried out in areas of increased flow. Full hull protection is recommended for older ships, or whenever the protective coating is insufficient or damaged. The required protection is achieved by the appropriate current density on the intended surface of the underwater part of the hull to be protected. In the case of full protection of the underwater part of the hull, the surface is calculated according to the following expression:

- The areas of the attachments are not calculated in this way and must be added. The required protective current density for hull attachments is higher and is determined by a separate expression.
- The current density depends on:
  - The quality of the protective coating,
  - The currents in the vicinity of the protected surface,
  - The type of surface being protected.

2.18. Protection of the underwater part of the ship using sacrificial anodes

Sacrificial anodes provide the ship's hull with protection against the negative effects of corrosion. Depending on the type of material of the vessel or maritime facility, zinc, aluminum and magnesium anodes are commonly used. The capacities of the anodes that are most often used are as follows:

- Zinc anode 780 Ah/kg,
- Aluminum anode 2820 Ah/kg,
- Magnesium anode 1100 Ah/kg.

The protective current density using zinc and aluminum anodes is approximately the same. Calculating the necessary masses of zinc and aluminum anodes per unit area, it follows that their volumes are also approximately equal. Anodes are made in shapes that provide as little resistance as possible to the circulating water. They consist of the anode mass and the supports with which they are attached to the substrate. Brackets are made of marine steel, stainless steel or aluminum. They are usually attached to a pre-prepared surface by welding or screws. The surface must allow good conductivity. Zinc anodes are commonly used for steel ships.

Magnesium anodes have found use on ships made of aluminum. Aluminum anodes are most often used to protect marine structures. The total current for the entire surface of the underwater part of the ship's hull is determined according to the expression:

- The number of anodes required to protect the underwater part of a ship's hull is the quotient of the total mass of the anodes divided by the mass of one anode.
- The protection of the underwater part of a ship using sacrificial anodes is usually expected to last for a period of between two and four years. During this period, approximately 80% of the anode will have worn out.
- The anodes are distributed on the ship's hull in a way that provides adequate protection to all parts of the underwater part of the ship. When placing anodes, the following principles must be taken into account:
    - Approximately 25% of the total mass of the intended anodes should be used to protect the ship's hull in the thruster area,
    - The rest of the anodes are distributed in the area of the rest of the ship, in the middle of the ship they are usually placed at a distance of 6 to 8 meters,
    - If the ship is expected to sail in areas where a higher protective current density is required, the distance between individual anodes should not exceed 5 meters,
    - Placed anodes on the bow and near the thruster should have the most favorable ones
    - Direction considering the expected water currents,
    - The anodes placed on the rudder sheet should be in the direction of the screw head and as far as possible above and below the wing radius of the screw,

- Place anodes in the areas of the suction baskets,
- On ships with multiple screws, if possible, place the anodes on the stern, or at the base of the stern in case this is not possible,
- In ships with special thrusters in the nozzle, it is necessary to properly protect the nozzle, and the anodes are placed around the outer rim nozzles,
- On ships built from non-metals, only metal parts are protected.

Verification of satisfactory protection of the underwater part of the ship's hull is obtained by measuring the potential. A reference electrode is used, usually zinc, which is placed as close as possible to the ship's plating. By measuring the potential difference between the reference electrode and a certain place on the ship, the size of the protective current is determined. Measuring points on the formwork must have good conductivity. The attached picture shows the arrangement of the anodes near the thruster on a ship with one thruster.

Protective coatings are selected based on the purpose of the tanks, which is especially evident in ships for transporting liquid cargo. It is important that the first coatings applied during ship construction are of good quality due to their demanding maintenance during operation. On ships transporting liquid chemical products, only protective coatings can be used, because the use of sacrificial anodes poses a risk of cargo contamination.

Tanks for which the use of sacrificial anodes is acceptable are most often protected in combination with protective coatings. Sacrificial zinc or aluminum anodes are usually used. The required protective current density is taken in relation to the condition of the surface to be protected, in the same way as for the underwater part of the ship's hull plating. The number of sacrificial anodes is determined according to the above expression, which applies to the hull, taking into account the period of time during which the tank is filled with liquid. However, the number of sacrificial anodes obtained in this way is approximate. There is a possibility that the liquid in the tank, which represents the electrolyte, contains certain impurities, which affects the magnitude of the total current, on the basis of which the number of sacrificial anodes is determined. The approximate total mass of sacrificial anodes is determined according to the following expression.

Sacrificial anodes must last until the end of the intended protection period. Usually, protection with sacrificial anodes is planned for a period of up to approximately four years. All impurities that appear on the surface of sacrificial anodes and in the electrolyte reduce their efficiency. However, it should be emphasized that the covering layers are porous and spongy and can be easily removed. The surface of sacrificial anodes should be cleaned when flushing tanks and in all cases where this is possible. In ballast seawater, the anodes remain constantly active, but with a decrease in the salinity of the electrolyte, the sacrificial anodes have a lower protection effect. parts in the form of large circles. The density of the windings in individual places will depend on the threat of corrosion. The durability of anodes in the form of wires is usually up to two years.

Conclusion

Since the system of cathodic protection using sacrificial anodes provides incomplete protection, the application of the system of cathodic protection with current was introduced. It is certain that surge current protection is one of the most important forms of metal protection against the negative effects of corrosion. Protection of the metal is achieved by the entry of the current from the outside into the metal. This requires a source of direct current, current regulation and an anode that can be soluble or insoluble. Insoluble anodes include lead, graphite, platinum, ferrosilicon, ferrosilicon and chromium, black platinized titanium, etc., while soluble anodes include iron, zinc, magnesium, aluminum, etc. Inrush current protection can be applied to protect all metals from corrosion in soil and aqueous solutions. Today, ships, underwater structures, oil pipelines in the ground, pipelines and other structures located either in the ground or in the water are protected in this way. Impulse current protection has found widespread use on ships, and it protects the underwater part of the ship's hull.

Impulse current systems were developed simultaneously with high-quality coatings. Many systems are such that they are complemented by applied high-quality coatings. As can be seen from the previous discussion, the number of sacrificial anodes depends on the surface area of the underwater hull, the age of the ship and the condition of the protective coating. In cases where a large number of anodes are required, their installation becomes economically unjustified. In these cases, protection of the ship's hull by impulse current is applied. Impulse current protection provides the possibility of regulating the protective current and using inert anodes that have a long-term durability. Inert anodes have a higher operating voltage, so a smaller number of anodes are required.

The protective current largely depends on the water in which the ship is located and on the operational condition of the ship. Therefore, unlike stationary facilities, devices with automatic potential regulation are used to protect ships. The power supply device for ship protection must be resistant to vibrations and other influences to which the ship is exposed during its exploitation.

The power source is a rectifier that converts alternating current into direct current. A protective current (Iz) is obtained from the specified source, and the potential is shifted towards the value (Ez). The current flows from the power source towards the inert anode, and the electrons towards the protected surface.

The anode is made of an inert material and is insoluble. Cathodic protection of a metal surface can be carried out in two ways; constant potential, and constant current. Constant potential cathodic protection is based on maintaining a constant potential (Ez) of the metal surface relative to the reference electrode. The constant potential is obtained from the device by manual regulation or automatic potential control. By manually adjusting the potential, the protective current density is equal to the limiting current density. Due to hydrodynamic changes, the corrosion current density increases, and to maintain the same potential value, a higher protective current density is required, which is adjusted manually or automatically. The control unit in automatic control maintains the potential of the metal surface constant relative to the reference electrode.

Anodes are attached to the ship's hull and are designed to provide as little resistance as possible when the ship is sailing. There is a layer of insulation between the ship's shell and the anode. The electrical current is supplied to the anode from the inside of the ship. Two types of inert anodes are commonly used to protect ships: attached to the ship's hull, placed in specially designed pockets on the ship's shell.

Anodes that are attached to the ship's hull are mostly made of Pb-Ag alloy. Active anode surfaces are placed in an elongated trapezoidal support made of synthetic material. Current is supplied to the anode inside the anode support via a conductor at the end of the anode.

Two narrow strips that represent the anode offer very low resistance and are flexible enough to follow the curvature of the ship's hull. Their disadvantage is that they represent an obstruction on the hull, which increases resistance, and they are also susceptible to mechanical damage.

Anodes that are placed in specially designed bearings on the ship's hull lie recessed in the ship's hull, so that their active surface is flush with the hull. The anode is placed in a specially designed housing, and the power supply is carried out in a similar way as with anodes attached to the ship's hull. These anodes are most often used on ships that are exposed to external mechanical loads, e.g. icebreakers.

The area immediately next to each flat-placed anode should be well protected from the effects of reaction products on the anode. Protection is achieved by placing a thick protective coating around the anode. The placement of anodes in an induced current system must be carried out very precisely, and any damage to the dielectric shield insulation must be repaired immediately. The active surface of the anodes and reference electrodes must be clean and free of paint. When painting the underwater part of the ship, the anodes are protected in an appropriate manner, usually by using grease.

The choice of anode depends on the cost, the durability of the anode and the total protective current required. The protective current density must be such that the hull of the ship is adequately protected. Inert anodes are distributed throughout the hull of the ship according to the same principle as sacrificial anodes. The difference is that there are much fewer inert anodes, and some types of ships have problems with the power supply.

Usually, inert anodes are placed in the engine room area due to the most convenient access to the anodes, which is also economically justified. It would be most effective to distribute them evenly along the entire ship's hull. In icebreakers and ships that pass through ice areas, regardless of the difficulties in implementation and greater economic costs, inert anodes must be distributed in this way. This ensures that the bow parts, where coating damage most often occurs, continue to be adequately protected.

Inert anodes are not placed on the rudder and propeller, but are connected to the ship's protection system by a cable connection or slip ring. Anodes in the surge current protection system are not placed at precisely specified distances, but depend on the ability to adjust the required surge current. On ships over 150 meters, the specified distance of the first anode from the propeller must not be less than 15 meters, while on smaller ships it is at least 5 meters.

Built-in reference electrodes are used to control the protective potential. A zinc electrode is most often used as a reference electrode. They have a constant potential and are slightly polarized. Their durability is at least ten years. No insulation protection is required around the reference electrodes. The reference electrode is placed at the point where the greatest voltage drop is expected. The distance between the electrode and the anode should be at least 15 to 20 m, while on smaller ships this distance is proportionally smaller. Recently, a larger number of smaller devices with their own regulation electrodes have been installed. This achieves more complete and uniform protection of the surface to be protected. In practice, it has been shown that it is more economical to install multiple power supply units than one device with a higher output current. On smaller ships, systems with a single automatic device are used, while on larger ships, multiple power supply units are usually used. A fault in the protection system must be visually and audibly reported at control points.

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