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Enhancing Ship Ballast Tank Corrosion Protection: A Comparative Analysis

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ABSTRACT

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Modern merchant ships face a major challenge in the form of corrosion in their ballast tanks, which directly affects the ships' economic lifespan. Sacrificial zinc anodes are added to ballast tanks, which are typically made of steel and coated with epoxy. This construction technique has essentially not changed over time. The objective of this research was to compare the traditional construction method with four alternative approaches to improve corrosion resistance and, in turn, increase the longevity of the vessel. These alternatives include. Using corrosion-resistant steel for ship construction, applying a new and more durable Tanker Structure Cooperative Forum 25 coating, and using a standard Protective Coatings Performance Standard 15 coating in conjunction with aluminium sacrificial anodes that last a lifetime. The impact of each alternative on the operational efficiency of the vessel was compared in this economic study, which also provides opportunity for future research on cost effectiveness. The goal of the analysis was to give shipbuilders and operators well-informed advice on how to choose the best corrosion protection plan to maintain the profitability, sustainability, and safety of maritime operations.

Keywords: Ballast tanks, Ship construction, Corrosion protection, Epoxy coating, Sacrificial anodes, Tanker Structure Cooperative Forum 25, Corrosion-resistant steel, Protective Coatings Performance Standard 15 coating, Economic lifespan, Maritime safety.

CONTENTS

LIST OF SYMBOLS AND TERMS

Al	Aluminium
AP	Anodic Protection
ASTMA131	Standard Specification for Structural Steel plate primarily used in ship construction.
Cl	Chloride
CRS	Corrosion Resistance Steel
Cu	Copper
DC	Direct Current
e^-	Electron
Fe	Iron
H_2O	Water
H2SO4	Sulfuric Acid
ICCP	Improved Current Cathodic Protection
IGC	Intergranular Corrosion
IMO	International Maritime Organisation
J	Joules/Energy
Kg	Kilograms
m	Meter
MIC	Microbiological Influenced Corrosion
Mm	Millimetre
NDF	Dry Film Thickness
NDFT	Nominal Total Dry Film Thickness
O	Oxygen
PSPC	Protective Coatings Performance Standard
SCC	Stress Corrosion Cracking
TCB	Total cost of ballast tanks
TSCF	Tanker Structure Cooperative Forum
WBT	Water Ballast Tank
Zn	Zinc
μm	Micrometre

1 INTRODUCTION

Corrosion in the ballast tanks of contemporary merchant ships is one of the biggest problems in shipbuilding and maintenance. For many steel structures, including storage tanks, pipelines, and bridges. Atmospheric corrosion is a well-known cause of metallic surface degradation; adding seawater to the mix creates an even more aggressive environment and amplifies the corrosion effect. However, most merchant ships that transport goods across the seven seas are made of steel. A ship keeps seawater in her ballast tanks when she is not carrying any cargo or is only partially loaded to maintain manoeuvrability and control draft, stress, and stability. Even though ballast tanks are essential to a ship's operation, their exposure to corrosion presents a significant problem for ship owners. Corrosion is very costly. The cost of corrosion to the U.S. economy alone in 1998 was $275.7 billion annually. (Koch et al., 2002.)

Maritime corrosion can pose a threat to safety. 90% of ship failures, according to statistics, were caused by corrosion (Melchers, 1999). One of the main reasons marine structural failures occur is corrosion. Corrosion causes fatigue failure, stress corrosion cracking, and a loss of structural strength both locally and globally. On ship structures, localized corrosion is frequently noticed. Ballast tanks are particularly prone to corrosion because of their frequent contact with saltwater, humidity, and an environment that is high in chloride even when they are empty. Due to the Oil Pollution Act of 1990's requirement for a double hull configuration (Assembly, 1990), it is challenging to maintain ballast tanks.

There is restricted access to ballast tanks, an unwelcoming atmosphere, little light, and difficult-to-reach sections. The unfavourable working conditions contribute to the high cost of the inside maintenance. The ship's weakest point is its double-hull ballast tanks. Therefore, one of the main factors in determining whether a ship will eventually reach the scrap yard or end its useful life is the amount of corrosion in its ballast tanks (Johnsons, 2006). Ballast tanks on ships nowadays are made of carbon steel and coated with epoxy. These help to lessen the effects of corrosion and, in certain cases, effectively hinder it (Wang et al., 2003). For decades, this kind of construction has been used with little to no modifications. The purpose of this study is to do a comparative analysis, limited to the development and construction of the upkeep of the ballast tanks, to compare this conventional method with a few viable alternatives.

1.1 Problem Statement

A significant factor limiting the vessel's lifespan is its construction and the level of corrosion on its hull and most importantly in the ballast tanks. However, regular inspection and maintenance should be made, but it’s quite difficult to do this for the ballast tanks, because they are situated in areas between the outer hull and the cargo holds which results to limited entry access. Nowadays ballast tanks on ships are typically made of steel and coated with epoxy which isn’t a sufficient method to prolong the lifetime of the vessel.

1.2 Aim and Objective

This research’s main goal is to carry out an investigation by comparing different methods available for the protection of the vessels ballast tanks against corrosion to prolong its lifespan.

1.2.1 Specific Objectives

1. Analyse the dynamics of corrosion specific to ship ballast tanks in different maritime environments.
2. Analyse different protection methods available and their role in preventing corrosion.
3. Examine the best way to use protection methods on ships.

4. Examine how much this method costs differently from other corrosion prevention strategies.
5. Include additional elements that fulfil the goals and expectations of the project's beneficiaries.

1.3 Research Question

What are the best possible available methods to protect or prolong the lifetime of ballast tanks against corrosion?

1.4 Motivation for The Research

Ballast tanks longevity and integrity are critical to the operational effectiveness and safety of marine vessels. These structures are seriously threatened by corrosion, so it is imperative to put effective preventative measures in place. This thesis has presented a thorough analysis of different corrosion prevention strategies, emphasizing the urgent need for a methodical and comparative study to determine the most effective, economical, and ecologically friendly options. This research intends to provide important insights into maximizing corrosion prevention in ballast tanks by investigating a variety of approaches, from conventional coatings to cutting-edge cathodic protection systems. The results of this study may not only help marine vessels last longer, but they may also have an impact on lower maintenance costs and improved environmental sustainability.

2 LITERITURE REVIEW

2.1 Introduction

This section outlines wide variety of studies that discuss the causes, effects, and mitigation techniques of corrosion in ballast tanks. It summarizes research results on material deterioration, electrochemical processes, and the efficacy of different cathodic protection systems and protective coatings.

2.2 Corrosion

Metals undergo physical and chemical processes called corrosion that change refined metal into more chemically stable compounds and change in their appearance, typically oxides, hydroxides, or sulphides. Particularly in the built environment, this oxidation or other reaction causes a slow, long-term deterioration in metal performance through thinning. Electrochemical reactions between the metal and its surroundings air, water, or both are the typical mode of corrosion processes. Therefore, it is believed that corrosion is a natural chemical phenomenon (Gopal, 2023). When most or all the atoms on a single metal surface oxidize, the entire surface becomes damaged and is referred to as general corrosion. Most metals are readily oxidized, meaning that they frequently lose electrons to oxygen and other chemicals in the air or water. Water or other moisture gets trapped between two electrical contacts that have an electrical voltage applied between them in electrolytic corrosion, which mostly affects electronic equipment. An unexpected electrolytic cell is the result. (Scherson, 2015, p. a.)

According to Scherson (2015) example consider a metal building like the Statue of Liberty, it appears robust and long-lasting but like almost everything made of metal, it can break down and become unstable when it interacts with other materials. Occasionally, corrosion is benign or even advantageous: the statue's greenish patina shielded the metal underneath from weather damage. But over time, corrosion seriously damaged the statue's interior. By 1986, the statue had reached its centennial, with nearly half of its iron frame rusting away due to its copper skin acting as an electrode like a giant galvanic cell (Scherson, 2015). The same process applies to the ship ballast tanks. The tanks are more like the statue of liberty and the epoxy coating is the greenish patina shielding the metal tanks carrying the sea water.

Figure 1: Corrosion (Scherson, 2015)

2.3 Types of Corrosion

In marine engineering, corrosion in ballast tanks is a major problem that can seriously jeopardize a vessel's structural integrity and operational safety. Ship components known as ballast tanks are crucial because they regulate draft and preserve stability under different loading scenarios. However, over time, tank materials may deteriorate due to exposure to corrosive environments like seawater and cargo residues. For the purpose of putting into practice efficient maintenance plans and reducing potential risks, it is essential to comprehend the types of corrosion that are common in ballast tanks. There are several types of corrosion that effect the ship ballast tanks due to different factors and the way they form. These are the most common ones you get in the ship ballast tanks or structures like ballast pipes. (Cemmedo, 2015.)

2.3.1 Uniform corrosion

When corrosive attack spreads uniformly across a significant portion of the surface area, it is referred to as uniform corrosion. There is general thinning until failure. Because uniform corrosion is relatively easy to measure and forecast, catastrophic failures are not as common. Often, it is objectionable solely because of how it looks. (AMPP, n.d.)

Figure 2: Uniform Corrosion (Estate, 2014)

2.3.2 Crevice Corrosion

When the protective film breaks, crevice corrosion happens. This is how cathodic reaction is realized: localized film fragmentation causes faster corrosion cracks. In addition to fractures in metal surfaces, non-metallic materials may also form in the spaces between metal surfaces in cases of crevice corrosion. Crevice corrosion, for instance, can happen between steel flanges at the locations where pipes with insulating flanges are connected to one another. The area near the cathode region where the crack mouth region is located is where corrosion is most effective. Corrosion can be caused by even tiny fissures up to one micron. It is also possible to say that a region of 2-3 mm in size, which is idle and low in oxygen, will experience crevice corrosion. (Cemmedo, 2015.)

Figure 3: Crevice Corrosion of Ballast Pump Impeller (Cemmedo, 2015)

The formation related crevice corrosion is explained as follows. Assume a bolt or rivet set with two steel plates welded to one another is submerged in seawater. Typically, the rate at which the corrosion phenomenon manifests itself on metal surfaces in solution is determined by the concentration of oxygen present in the solution. Using two plates, to determine the cathodic oxygen content of the solution in the area where anodic and initially incoherent reactions start. (Cemmedo, 2015.)

2.3.3 Pitting Corrosion

A pit, hole, or cavity that develops in a small area or point is known as pitting corrosion. Metals and alloys like steel, iron, aluminium, and more are susceptible to pitting corrosion. It is typically limited to regions. It is fast to penetrate, quick to attack, and hard to spot. The most frequent places for it to happen are when the passive coating layer is chemically or physically attacked. As a result, the substrate becomes vulnerable to being attacked by water or corrosive solutions. It is common for adjacent materials to appear unaffected. Pitting corrosion can be disastrous for roof systems or any metal structure if it is not controlled. It is often overlooked because it happens quickly. This makes it one of the most dangerous types of corrosion. (Coatings, 2016.)

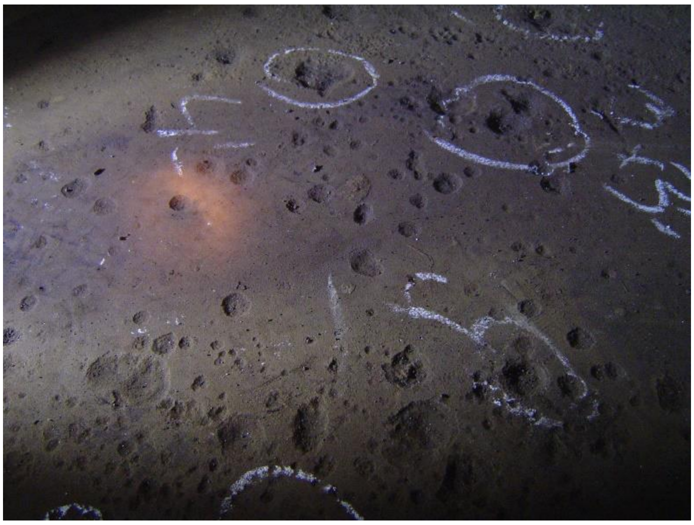

Figure 4: Pitting Corrosion (Microbiology, 2011)

A small amount of rust, or corrosion product, covers up the pits or holes. A pit, cavity, or tiny hole form when an anodic reaction in a small area (exposed metal) is sustained by a cathodic reaction in a large area (coating). The metal still undergoes oxidation even in the absence of oxygen. Severe pitting corrosion occurs when the large cathode places a high electron demand on the small anode. It will occur quickly, be subtle, and have very negative consequences. While damage is occurring deep within the metal structure below, only a small area of rust is visible on the surface. (Microbiology, 2011.)

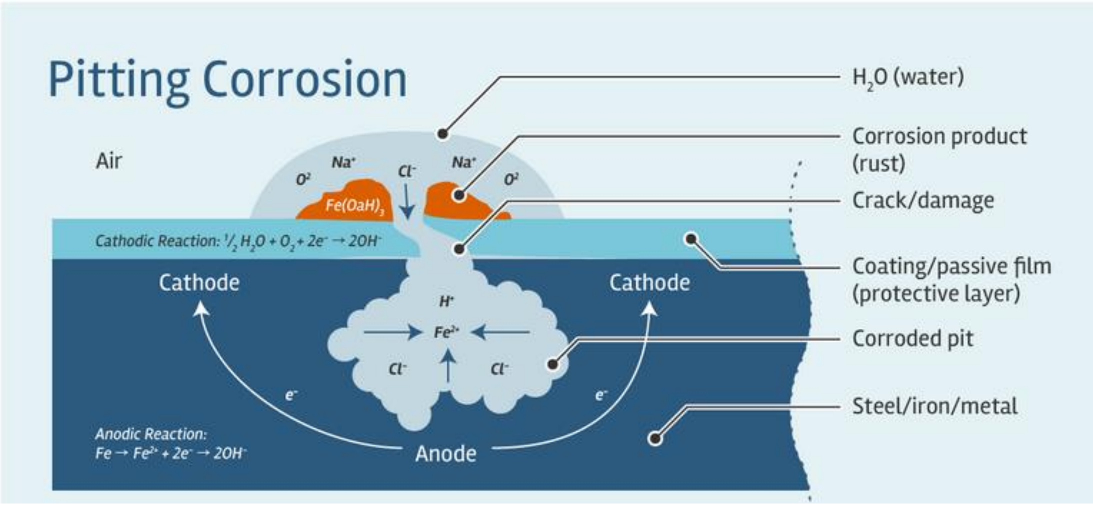

Figure 5: Formation of Pitting Corrosion (Coatings, 2016)

2.3.4 Galvanic Corrosion

Bimetallic or galvanic corrosion is an electrochemical process in which a metal that meets an electrolyte corrodes more readily than another metal. When two different metals are electrically connected and submerged in a conductive solution, galvanic corrosion takes place. While the other metal, the anode, corrodes, the first, the cathode, is shielded. In comparison to the rate at which the metal is uncoupled, the rate of attack on the anode is accelerated. Aluminium will corrode more quickly than carbon steel, for instance, if they are connected and submerged in seawater, but the steel will be protected. (LTD, 2024.)

Figure 6: Galvanic Corrosion (Wheeler, 2018)

Metals can be protected against Galvanic Corrosion by following these methods.

- Choosing materials with comparable capacities for corrosion.
- Insulating the two metals from one another to break the electrical connection.
- Coating both materials. The cathode's coating is the most crucial component and needs to be in good condition to prevent galvanic corrosion from getting worse.
- Separating the two materials by placing a spacer of the appropriate size.
- Putting in place an anode sacrificial to both metals.
- Introducing an environmental corrosion inhibitor.

If these steps are impractical, maintaining a large anode to cathode area more than 10 can help reduce the rate of attack. As an alternative, the anode could have a suitable corrosion allowance built into its design. In some environments, galvanic action can lead to preferential corrosion of welds. For instance, carbon steel weld metal may be severely corroded in seawater while the parent material nearby remains unaffected. (LTD, 2024.)

2.3.5 Selective Corrosion

Selective corrosion, also known as selective leaching or dealloying, is the preferential attack of a specific alloy component due to an electrochemical oxidation-reduction (redox) process in the presence of electrolyte. Both single-phase and multi-phase alloys are susceptible to selective corrosion. Components with a significant discrepancy in their electrode potentials, such as copper and zinc, make up alloys that are vulnerable to selective corrosion. In the electrolyte, the component with the lower electrode potential (higher position in the electrochemical series table) will undergo anodic reaction and dissolve, whereas the component with the higher electrode potential will undergo cathodic reaction (reduction). Plug-type (localized) or uniform selective corrosion are both possible. (Kopeliovich, 2023.)

Figure 7: Selective Corrosion (Moriber, 2020)

Figure 8: Selective corrosion on shell plate (Moriber, 2020)

The loss of zinc from *Brasses (copper-zinc alloys) due to selective corrosion, also known as dealloying, is known as dezincification. When the zinc content in brass exceeds 15%, dezincification takes place. An element with chemical activity is zinc. Its standard electrode potential (-0.763) is extremely low. Copper has a substantially higher standard electrode potential (+0.337). The dezincification process is driven by the difference between the potentials. (Kopeliovich, 2023.)

<u>Potential dezincification mechanisms:</u>

Zinc selectively dissolved only in accordance with anodic reaction.

Zn is equal to Zn2+ + 2e-.

Copper and zinc dissolve simultaneously in accordance with the anodic reactions

Cu = Cu2+ + 2e- and Zn = Zn2+ + 2e-,

and copper is then redeployed by the cathodic reaction.

Cu2+ + 2e- = Cu.

<u>Strategies to stop dezincification:</u>

- Enhance the aggressive environment by reducing the amount of oxygen and chloride, reducing acidity, and avoiding stagnant water.
- Use Copper-nickels or brass with a low zinc content (less than 15%);
- Put cathodic protection to use.
- Employ brassieres with inhibitory additives (0.05% As, 0.05% Sb, 1% Sn, and P).

2.3.6 Erosion Corrosion

The degradation Corrosion is the result of erosion and corrosion working together, and it is brought on by any turbulent fluid flowing quickly across a metal surface. Pitting, which is often found on the inner surfaces of pipes, is the main cause of turbulence. The rate of erosion increases in turbulent conditions and can result in leakages in tubes and pipes. The corrosive action of the flowing fluid is combined with the fluid's velocity and the physical effect of the fluid pushing against the surface when it passes through a pipe. This leads to an expedited loss of metal. Usually, the protective film on the metal is the first thing the fluid erodes. When the film is removed, the metal becomes vulnerable to corrosion. In regions of constriction, this kind of corrosion is frequent. These include regions with blockages, pump impellers, inlet ends, and other locations with high flow rates. (Erosion Corrosion, 2019.)

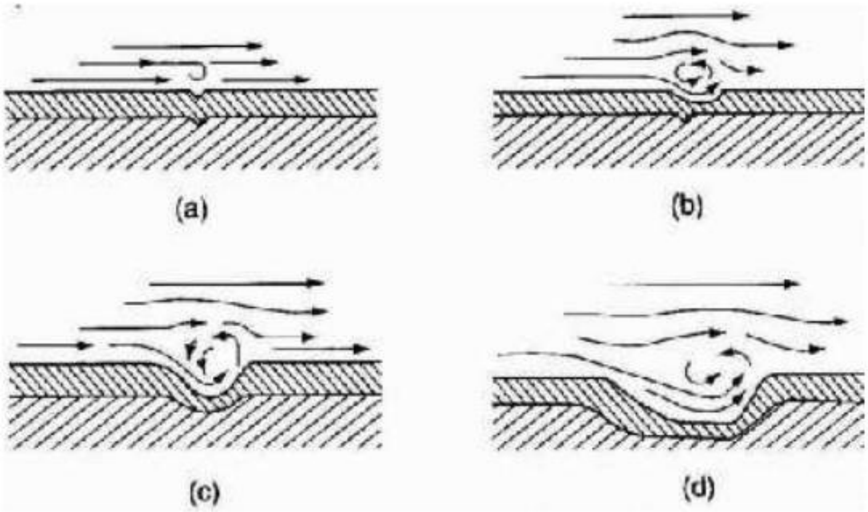

Figure 9: Formation of Erosion Corrosion (Cemmedo, 2015)

Any of the following techniques can stop or lessen erosion and corrosion:

- Simplify the piping to lessen the fluid's turbulence in the tube.
- Lower high-flow velocities by regulating the fluid's velocity.
- Make use of materials that resist corrosion.
- Make use of cathodic protection and corrosion inhibitors.
- Make certain that all of the pipes have been cleared of debris.
- To prevent constrictions, replace the piping system's sharp angles with softer ones.
- Decrease the fluid's dissolved oxygen content.
- Modify the fluid's pH level.
- Alter the alloy of the metal.

Figure 10: Erosion Corrosion of ship ballast line (Cemmedo, 2015)

As "cavitation" stops, a unique type of erosion corrosion phenomenon occurs. Should there be vapor or gas bubbles in the fluid, any obstruction could cause the pressurized gas on the metal surface to burst, leading to wear and tear in that area. This phenomenon is typically observed in hydraulic turbines, as demonstrated by the propeller and pump pallet of the ship. The process of cavitation involves the vaporization of liquid at high flow rates due to the formation of a vacuum in some areas, or the separation of dissolved gases in the liquid phase.

Low pressure gas bubbles consequently form in the liquid. Figure 11: Occurrence of Cavitation Eventsillustrates the cavitation events that occur.

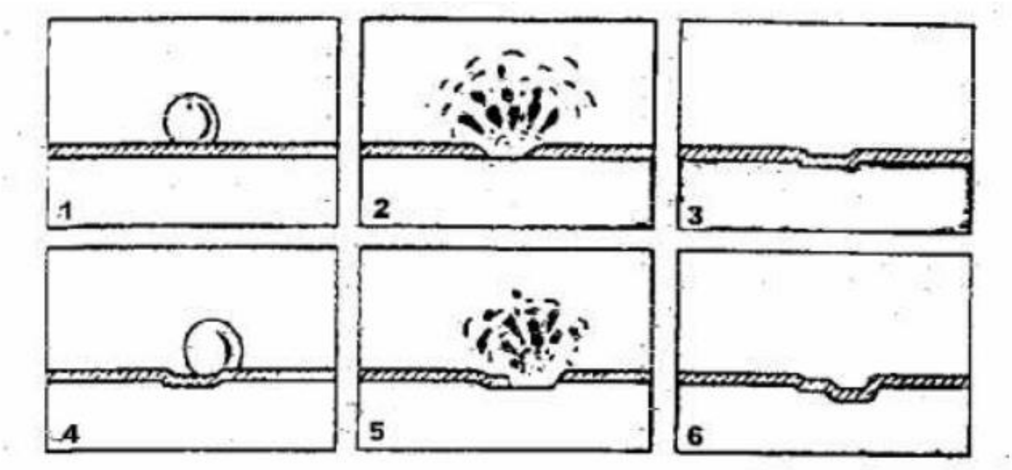

Figure 11: Occurrence of Cavitation Events (Cemmedo, 2015)

2.3.7 Atmospheric Corrosion

Typically, climatology-related terms like rainfall, relative humidity, pollutants, winds, aerosol transport, temperature, etc. are used to describe atmospheric corrosion. In general, temperature, the amount of pollution in the atmosphere, the length of time moisture is in contact with the surface, and the chemical makeup of the substrate such as carbon or stainless steel all affect how quickly atmospheric corrosion occurs. (University, 2020.).

Figure 12:Atmospheric Corrosion of Flange (Flange Band Protectors, n.d.)

2.3.8 Intergranular Corrosion

The corrosion that occurs preferentially or locally either alone the grain (crystal) boundaries or right next to them is known as intergranular corrosion (IGC), sometimes known as intergranular attack (IGA). On the other hand, most of the grains continue to be mostly unaffected. Even though there is little metal loss, IGC can result in catastrophic equipment failure. In the presence of corrosive media, IGC is a frequent form of alloy attack that causes a loss of ductility and strength. It is important to distinguish between IGC and stress corrosion cracking (SCC). For SCC to occur, stresses whether applied or residual must act cyclically or continuously in a corrosive environment, causing cracks to follow an intergranular path. The anodic dissolution of regions weakened by the alloying elements, second phase precipitation, or regions with isolated alloying or impurity elements are the causes of the ICG localized corrosion at grain boundaries.

Figure 13: Intergranular Corrosion (Jayasinghe, 2022)

Large cathodic areas aid in the anodic dissolution process, while the remaining exposed surface usually serves as the cathode. In most cases, the cathode to anode ratio is larger than one. Grain size, the distribution of harmful alloying and impurity elements, and the volume fraction and distribution of electrochemically active phases are some of the variables that affect it. The dominant corrosion mechanism determines the corrosion rate, and the kinetics of dissolution can be influenced by species diffusion to or from the anodic front. The formation of a comparatively homogeneous and uniform depth of attack is an important feature of IGC. Grain dislodging, also known as grain dropping, is the result of the breakdown of grain boundaries. Most of the weight loss seen following IGC exposure is caused by grain dropping, therefore corrosion rates can be several orders of magnitude higher than during general corrosion. (Jayasinghe, 2022.)

Appropriate annealing and quenching procedures carried out at the fabrication shop or mill can lessen the vulnerability of nickel-rich chromium-bearing alloys and stainless steel to IGC. Dissolved molybdenum carbides, nitrides, and chromium carbides, along with their pre-precipitation forms, remain in solution during the quenching process when these treatments are successfully completed. (Intergranular Corrosion: What It Is and How To Stop It, 2022.)

2.3.9 Microbiological Corrosion

Figure 14: Microbiological Influenced Corrosion (Rope, 2020)

Microorganisms start, assist, or speed up a corrosion reaction on a metal surface through an electrochemical process. It generally entails the reduction of external electron acceptors and the oxidation of metallic iron to Fe (II). While the process is accelerated by a variety of microorganisms in an oxide environment, it would take a very long time in an anoxic environment to reduce the proton alone without the assistance of microorganisms. Localized corrosion is primarily caused by microbiologically influenced corrosion. Aerobic bacteria can convert oxides and sulphur compounds into elemental sulphur in sulphate of all types, including Thiobacillus trioxidanes. Oxygen is a necessary environment for the activity of these bacteria. sulfuric acid is produced when oxidized sulphur is exposed to it. (Kadukova, 2018.)

This is how MIC forms.

Microorganisms' physical presence and metabolic activity alter the surface's electrochemical characteristics. Microorganisms procreate and establish colonies. The entire surface cannot be covered by colonies. The oxygen content of the colony is the same regardless of its surface area. These are known as various cell concentrations and are useful in preventing corrosion. The anode is also formed directly next to a colony beneath the cathode area. These variations on metal surfaces result in variations in electrical potential, and these variations collectively lead to the formation of MICs. (Rope, 2020.)

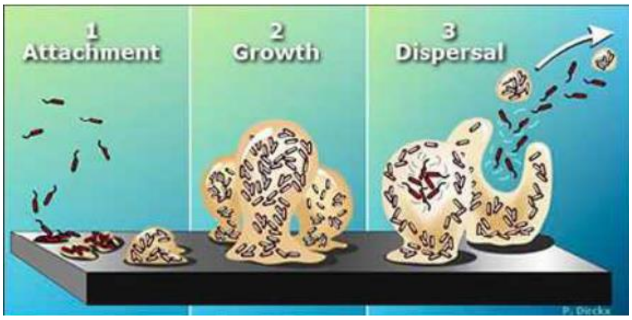

Figure 15: Formation of MIC (Rope, 2020)

2.3.10 Hydrogen Embrittlement

The brittleness of a material brought on by hydrogen influence is known as hydrogen embrittlement. The dissolution and diffusion of hydrogen in the microstructure of metal pipes and infrastructures is the cause of this phenomenon. When hydrogen is combined with mechanical stress, it forms tiny cracks that gradually enlarge. (Hydrogen, n.d.)

Figure 16: Hydrogen Embrittlement (Williams, 2005)

Normally, hydrogen can only penetrate metals such as hydrogen ions or atoms. Thus, unlike molecules, where atom pairs are firmly bound to one another, gaseous hydrogen is not absorbed by metals at room temperature. But as the temperature rises, the molecules tend to split up into individual atoms, which makes absorption possible at temperatures related to heat treatment or petroleum refining, for instance. (htt, 2014.)

Higher rates of absorption are found in molten material, which implies that casting and welding processes may present unique chances for hydrogen to enter metallic materials. Reactions related to processes like cathodic protection, electroplating, and corrosion can also produce hydrogen ions. As a result, there is plenty of room for hydrogen to enter metal components. (Park, 2023.)

Figure 17: Hydrogen Embrittlement of Bollard (Cemmedo, 2015)

How to Avoid Embrittlement of Hydrogen by reducing the amount of metal-to-atomic hydrogen contact can help avoid hydrogen embrittlement. Environmental factors should be managed in potentially corrosive services to prevent reactions on the metal surface from producing hydrogen ions. In real terms, this means that the metal needs to be shielded from environments that promote corrosion, such as by applying coatings, or it needs to be kept out of such situations. Processes that involve acid pickling or that provide cathodic protection should have their electrochemical conditions regulated to prevent the release of hydrogen at the component surface. Heating the metal to a temperature between 100 and 150 °C will remove any hydrogen atoms that have gotten inside. (Park, 2023).

2.4 Additional Damages Caused by General Corrosion

In addition to the material loss from the drill pipe, other losses from corrosion include:

- Product loss to the environment escaping from the pipe because of the puncture,
- Pollution from fluid released into the environment or negative effects,
- Fuel cases that pose a risk of fire or explosion
- Epidemics that could break out in the water city.
- Lost revenue and losses from poor business management
- and labour costs associated with replacing outdated pipes with new ones that had to be removed.

2.5 Techniques for Corrosion Loss and Reduction

Marine vessels ballast tanks are crucial parts that are required for stability maintenance and buoyancy control. These tanks are necessary for safe and efficient navigation during loading and unloading procedures. However, the marine environment poses a serious risk to the structural integrity of ballast tanks due to its exposure to corrosive seawater. Corrosion-induced material loss is one persistent issue in these tanks, necessitating a focused investigation of corrosion assessment and reduction techniques.

It is very difficult to account for corrosion loss costs. Aside from these difficulties brought on by labour and material losses, corrosion was also a result of identifying certain secondary invisible losses. Corrosion resulting from direct labour and material loss must be factored into other corrosion-related emerging losses. According to Fahad and Rana (2017), five items can be used to categorize indirect losses brought on by corrosion.

2.5.1 Shutdown of Facilities

The financial impact of facilities being shut down for corrosion-related repairs is significant for maritime operators. Production is directly impacted when a vessel is taken out of service for repairs, which leads to lost revenue and higher operating costs. In addition, schedule disruptions brought on by repair downtime may result in fines for cargo delivery delays or breached contracts. To make matters worse financially, the expense of replacing rusted pipelines inside ballast tanks must be considered. It involves paying labor costs for installation and testing in addition to the cost of purchasing new supplies and machinery. Furthermore, the total financial losses may increase due to indirect costs like fines imposed by regulations for breaking safety or environmental standards. Therefore, to reduce disruptions and maximize operational efficiency in maritime operations, proactive maintenance strategies and investments in corrosion prevention technologies are critically needed. This is highlighted by the shutdown of facilities because of corrosion-related issues. (Fahad & Rana, 2017.)

2.5.2 Loss of Product

If the product is lost during the period until the difference has been reached, the event is concerned, if the corrosion of the drilling pipe or tank is the cause. These losses must be considered corrosion losses. In addition to causing pollution to the environment and causing product loss, flammable products pose a fire risk. One such example is when fuel leaks into the ground from gas stations due to fuel tank perforations. (Fahad & Rana, 2017.)

2.5.3 Loss of Efficiency

A boiler may develop because of corroder product buildup, which reduces heat transfer capacity. Rust buildup can also clog water supply pipelines, necessitating an increase in pumping power. Internal combustion in a car engine. Loss of a vital dimension in the cylinders and piston rings. (Fahad & Rana, 2017.)

2.5.4 Contamination of the product

Products that are corroded lack mechanical strength. There is a very high chance that the product will be tampered with. As an illustration, the soap industry uses copper salt to speed up the production of soap and reduce the amount of time it needs to be stored before being sold. a tiny quantity of copper accumulated through copper pipe corrosion. It is not advisable to use load equipment in the food, beverage, or pharmaceutical industries due to the toxic nature of lead and the products it corrodes. Lead pipes are unsafe to transport soft water for drinking purposes for the same reason. (Fahad & Rana, 2017.)

2.5.5 Over design

Overdesigning is a common occurrence that results in significant losses. When designing underwater pipelines, water tanks, reaction vessels, boilers, condenser tubes, marine structures, etc., young engineers typically use far more material than what is necessary for regular operation to apply pressure stress and ensure life safety. This is caused by a lack of knowledge regarding the rate of corrosion, the name of the materials' environment quality, the method of controlling corrosion, etc. For instance, overdesign is frequently seen in underground oil pipelines. (Fahad & Rana, 2017.)

2.6 Corrosion mitigation methods

Corrosion, which is the slow degradation of materials because of chemical reactions with the environment, is a major problem in many industries, including manufacturing and infrastructure. Corrosion is a widespread problem that not only jeopardizes the structural integrity of materials but also poses a significant risk to safety and causes significant financial losses. As a result, scientists and engineers have created a variety of mitigation techniques to stop corrosion. These techniques use cathodic protection, protective coatings, and alloying to increase the longevity of materials and guarantee the dependability of vital machinery and infrastructure. In today's world, knowing and putting these mitigation strategies into practice are crucial to protecting assets and ensuring the operation of critical systems. Most of the time, thicker or more expensive materials must be used during design because it is impossible to fully estimate the initial corrosion rate. Many strategies, some of which are listed below, have been developed to minimize corrosion losses as much as possible. (Eliasson, 2003.)

2.6.1 Painting and Coating

A mixture or dispersion of opaque pigments or powders in a liquid or vehicle is referred to as paint. Other substances that function similarly to paint, such as varnishes and inorganic binders, are also referred to as coatings. The first line of defence between the building and the environment is made up of paints and coatings. Choosing the appropriate paint or coating requires an understanding of the formulations and components. The three main parts of an organic coating are the pigment, the resin (binder), and the solvent. Additives, the fourth component, can be added to change or enhance processing, appearance, or performance-related attributes. Not every coating has all four ingredients. There is solvent- and pigment-free clear coatings available, but never binder-free coatings:

Figure 18: Common components in a coating. (Dean, 2021)

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- Binders are the part of the coating that form the film; they are also referred to as resin, polymer, or vehicle.
- Pigments comprise the colouring and filler substances. The heavier, solid part of the pigment that sinks to the bottom of containers after a long time is called the insoluble pigment.
- The volatile diluents or thinners that evaporate during curing are known as solvents. The term "coatings solids" can refer to the remaining pigment and binder. The thickness of the coating films is directly influenced by the coating solids. (Dean, 2021.)

2.6.2 Stainless steels

Stainless steel consists of iron, chromium, and occasionally nickel and other metal alloy that resists corrosion. Steel is a carbon and iron alloy. Steels with at least 10.5% chromium, less than 1.2% carbon, and additional alloying elements are known as stainless steels. You can improve the mechanical qualities and resistance to corrosion of stainless steel by adding additional elements like manganese, nickel, molybdenum, titanium, niobium, and so on. (Hong, 2014.)

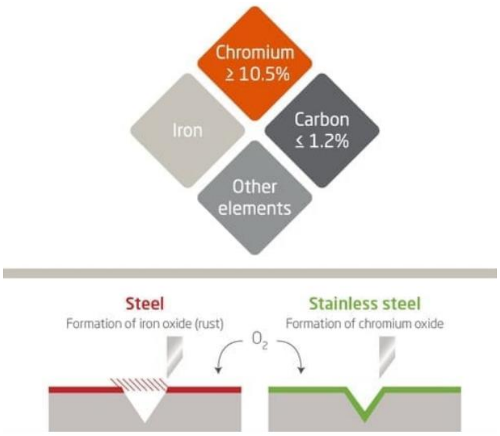

Figure 19:Formation of Steel and Stainless Steel (Hong, 2014)

2.6.3 The use of Inhibitor

Chemicals known as corrosion inhibitors reduce the rate at which a material, like a metal, is attacked in a hostile environment when they are added in tiny amounts. The rate at which a metal corrodes in that environment is slowed down by the corrosion inhibitor. Corrosion inhibitors stop metal corrosion through passivation, poisoning, precipitation, and surface adsorption. Inhibitors, which are frequently applied without interfering with a process, are used internally with carbon steel pipes and vessels as a cost-effective corrosion control substitute for stainless steels and alloys, coatings, or non-metallic composites. Corrosion inhibitors are widely used in the following industries: water treatment, chemical manufacturing, heavy manufacturing, oil and gas production and exploration, petroleum refining, and product additive industries. (Umoren, 2022.)

2.6.4 Anodic Protection

A potential-control electrochemical method called anodic protection (AP) can stop a metal from corroding in corrosive conditions like sulfuric acid (H_2SO_4). Anodic protection is a type of corrosion protection intended to shield metals from extreme corrosive conditions where the metals are either too basic or too acidic. The metal to be protected in this technique must exhibit passivity at relatively low current densities. Anodic protection works by covering the metal's surface, also referred to as the substrate, with a layer of protective coating. Experts in corrosion protection use regulated electric current to charge the protective film using an anode to produce the anodic layer on the metal's surface. By utilizing an external power source, the current can change how thick the protective layer is. (Perez, 2004.)

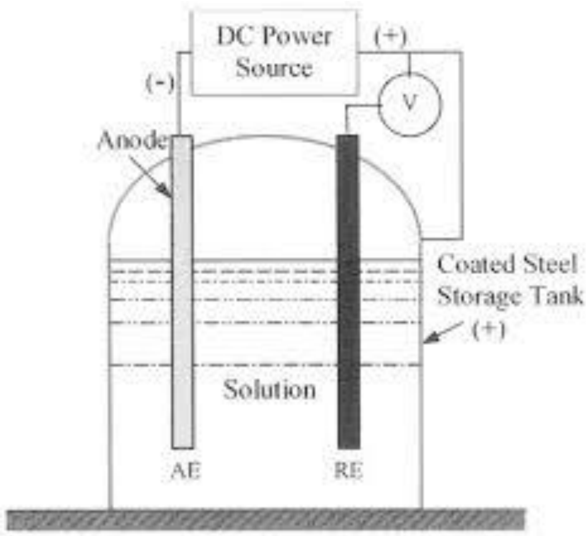

Figure 20: Anodic Protection (Perez, 2004)

2.6.5 Cathodic Protection

The method's foundation lies in turning active regions of a metal surface into passive ones or turning them into the cathode of an electrochemical cell. By supplying current, cathodic protection is achieved, the metal's potential is decreased, and the corrosion attack stops. One can accomplish cathodic protection by either:

- Cathodic sacrificial anode protection

  Applying cathodic protection is as simple as connecting the metal that needs to be protected to an easier to corrode metal that will serve as the anode. The metals magnesium, aluminium, and zinc are frequently utilized as anodes. To protect the cathode, the most active metal which is also the least noble becomes the anode for the other metals and gives up metal through corrosion. Since sacrificial anodes have a lower driving voltage than impressed current anodes, it is necessary to distribute them widely and place them in closer proximity to the area that needs to be protected. Positively charged metal ions exit the anode surface while electrons exit the cathode surface because of the potential difference between the anodic (less noble) and cathodic (steel) areas. The reaction at the anode surface for aluminium alloy anodes is $4Al \rightarrow 4Al^{+++} + 12e^{-}$. (Cathwell, 2023.)

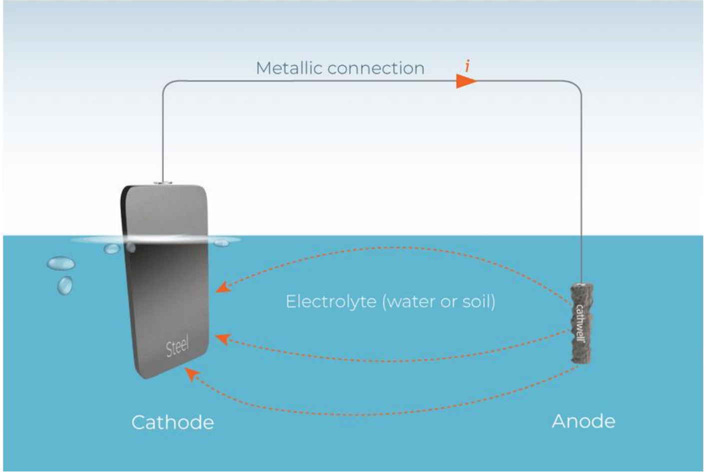

Figure 21: Sacrificial Anode Protection (Cathwell, 2023)

- Improved current cathodic protection, or ICCP as it is commonly known. An external electrical power source, known as a control panel or regulated DC power supply, is used by ICCP systems. The current required to polarise the surface that needs to be protected is supplied by the control panel. Specially made inert anodes, which are often made of conductive material that resists easily dissolving into metallic ions and instead supports alternative anodic reactions, distribute the protective current. Under favourable seawater environmental circumstances, the main anodic reaction leading to the development of chlorine gas at the anode surface will be the oxidation of the dissolved chloride ions: $2Cl^- \rightarrow Cl_2 + 2e^-$. The breakdown of water will be the main anodic reaction in low salinity waters. $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$. (Cathwell, 2023.)

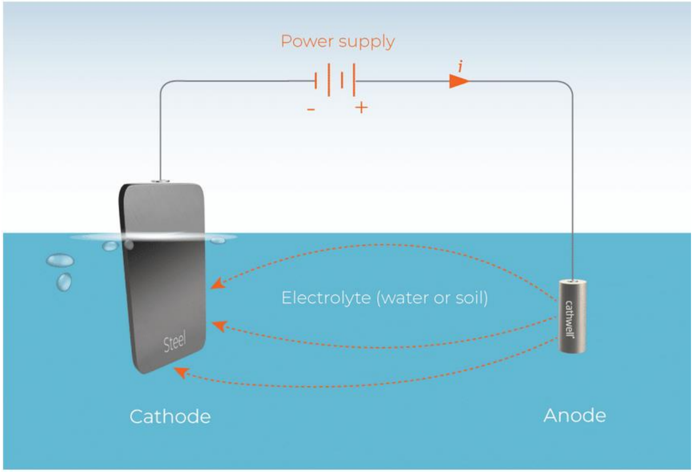

Figure 22: ICCP Protection (Cathwell, 2023)

2.7 The Effects of Corrosion

The effects of corrosion are very varied and severe; for example, a simple piece of equipment or building may experience a reduction in reliability and efficiency when exposed to a metal mass. Even in cases where there is relatively little metal destruction, there could be multiple malfunctions and costly replacement requirements.

3 RESEARCH AND METHODOLGY

3.1 Introduction

An important factor for investors in a development project is how the data is presented. The approaches and research methods the researcher employed for the analysis are covered in this section. The theoretical framework that includes the techniques and approaches used in earlier research, along with the findings and significance of those studies, is referred to as research methodology. Research techniques examine the instruments and information gathering utilized in this examination. The section also focuses on the research strategy the researcher employed to achieve the project's stated goals and objectives. Along with a summary of the topic, it will conclude with the researcher's ethical guidelines.

3.2 Research Methods

This research investigates and analyse the best affordable and effective techniques to consider when building or renovating a ballast tank on vessel in prevention to corrosion. The research was structured into phases that were assessed as it went along to make gathering data easier. A model for the overall cost of ballast tanks is created to evaluate the various options. After that, a sensitivity analysis is performed to account for uncertainties. With the aid of Microsoft Word, Excel, and other useful software, data was further investigated. (Indeed, 2023.)

3.3 Research Methodology Study Overview

A framework was employed to guide the researcher on what procedure to follow in getting the best results for the best protection method by comparative approach.

Firstly, the research got 5 different cases on how most vessels ballast tanks are constructed and used them as his reference point into employing the best strategies in mitigating the corrosion of ballast best. Secondly, the research did a comparative analysis between the different methods used in the different cases and got the best suitable methods for the preventative and longevity of the ballast of tanks. Lastly, the best suitable methods were obtained and presented as the best methods for ballasts tanks construction when looking for longevity, more friendly and sustainable methods. However, the researcher also presented some calculation equations in obtaining the cost when constructing the ballast tanks for future research.

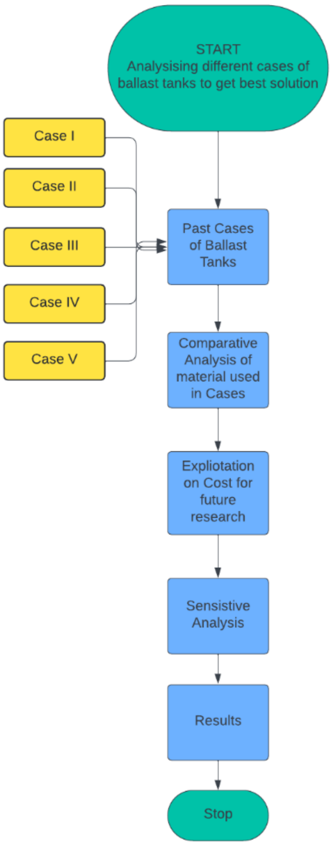

Diagram 1: Research Methodology Framework (Kamapunga, 2024)

4 MATERIAL SELECTION AND CALCULATIONS

4.1 Introduction

This section will conduct and discuss the process and outcomes of selecting appropriate material and techniques for longer life lasting ballast tanks. A key component of engineering and design, material selection affects the functionality, robustness, and affordability of structures and products. While selecting materials for a particular application, engineers must carefully consider aspects like mechanical properties, corrosion resistance, and environmental compatibility. Through careful material selection, designers can maximize functionality, extend product life, and reduce maintenance needs—all of which contribute to better outcomes across a range of industries, from electronics and construction to automotive and aerospace. The choice of materials has a significant impact on how well-functioning and dependable the structures and goods that make up our contemporary world are. It will look in different past case and see which method or technique is best for the prevention method. (W.D Callister, 2006.)

4.2 Case I

We use Case I as an example of a standard tank built today. It is made of regular grade A steel, has a thickness of 14 mm, is coated with standard PSPC[15] coating (IMO, 2006), and has zinc sacrificial anodes installed. Such a tank lasts for about five years (Verstraelen et al., 2009); after that, the coating begins to deteriorate and corrosion shows, necessitating eventually the replacement of the steel and paint restoration. It is necessary to replace the anodes every five years.

4.3 Case II

The primary component in case II is corrosion allowance. The maximum steel thickness loss permitted by the classification society is known as the corrosion allowance; it denotes the amount of corrosion that can occur over a ship's lifetime without jeopardizing the structural integrity of the vessel. In dry dock, steel will be replaced once its thickness has dropped to 80% of its original value. Even the most conservative classification societies' current corrosion allowances are only just sufficient for a vessel with a 20-year design life. (Gratsos et al., 2009). Since a standard $PSPC_{15}$ coating is applied and anodes need to be changed every five years, case II has been selected to allow for an extra 3 mm of corrosion allowance.

4.4 Case III

In Case III, ships are coated with the $TSCF_{25}$ coating, which is presently experimental, over 14 mm grade A steel. With better substrate preparation, better application conditions, and a thicker coating, this coating system is predicted to last 25 years, or the economic lifetime of the ship (SHELL, 2000). As a result, coating repair requirements are decreased, and steel replacement is no longer necessary. As the area subjected to corrosion attacks decreases, so too will the number of sacrificial anodes used. There will only be one replacement of the anodes every ten years.

4.5 Case IV

According to IMO $PSPC_{15}$ (IMO, 2006) the tanks in case IV are made of corrosion-resistant steel (CRS) and painted with an aesthetically pleasing white coating. Repairing coatings is still necessary, but less so. Anodes grow obsolete and are not utilized.

4.6 Case V

Once more, the case V tanks are made of regular grade A steel and coated with a standard $PSPC_{15}$ epoxy. Aluminium sacrificial anodes with enough mass to last the entire 25-year economic life of the chosen model provide cathodic protection.

4.7 Summary of the Case's

In the below table the researcher has summarized the different case in a table format for easy comparative between the different methods.

Table 1: Summary of the five Cases (Kamapunga, 2024)

	Case I	**Case II**	**Case III**	**Case IV**	**Case V**
Steel	Grade A	Grade A	Grade A	Corrosion Resistance	Grade A
Paint System	IMO PSPC 15	IMO PSPC 15	$TSCF_{25}$	1 coat white epoxy	IMO PSPC 15
Thickness	320µm	320µm	350µm	160µm	320µm
Paint Quality	Pure Epoxy	Pure Epoxy	Pure Epoxy	Pure Epoxy	Pure Epoxy
Anodes	Yes (Zn)	Yes (Zn)	Yes (Zn)	No	Yes (Al)
Replacement of the Anodes	Every 5 years	Every 5 years	Every 10 years	N/A	Every 25 years
Coating Repair	Yes	Yes	Yes	Yes	Yes
Increased Scantlings	No	Yes	No	No	No
Steel Replacement	Yes	N/A	N/A	N/A	Yes

4.8 Type of Steel to be used.

Corrosion Resistance Steel and Grade A Steel were the two types of steel used in the construction of the cases. Although they both have structural functions, their corrosion resistance is very different. Corrosion Resistance Steel is perfect for applications in corrosive or harsh environments because it provides increased protection against environmental degradation. On the other hand, even though Grade A steel is strong, it might need extra precautions in certain situations (Chan, 2015). The project's unique needs and longevity requirements will determine which option is best.

4.8.1 Grade A Steel

The hull structure and platform of shipbuilding are constructed from grade A steel plate. The common tensile strength steel is grade A shipbuilding steel plate. It offers strong corrosion resistance, greater strength, good toughness, processing, and welding qualities. ASTMA131 When building a ship with a hull structure weighing less than 10,000 tons, grade A steel plate can be utilized. These ships are typically used for coastal and river navigation. (BBN, 2024.)

Specifications for Grade A shipbuilding steel plates:
Width: 1200 mm to 4000 mm, Thickness: 4 mm to 260 mm
3000 mm to 18000 mm in length.

4.8.2 Corrosion Resistance Steel (CRS)

Corrosion Resistant Steel, or CRS TMT Bars are composed of a variety of elements that resist corrosion, including phosphorus, copper, and chromium. Because of the high level of corrosion resistance in CRS TMT Bars, they can be used for construction projects involving large dams, bridges, and coastal areas. CRS Bars are an affordable corrosion solution that will help the building resist corrosion and extend the building's structural life. The CRS TMT Bar's ability to be bent and re-bent around minuscule mandrels is an additional benefit. Early in the building process, it will slow down the rate of corrosion, strengthening the structure and increasing its resistance to earthquakes. (Karuppiah, 2001.)

4.8.3 Comparative Analysis

According to research done before on a large ore carrier test ship. The upper deck and its longitudinal members served as the test sections. Tar epoxy with 150 μm×2 coats were the coating specification. This ship's route primarily consists of a round-trip journey between Brazil and the Philippines. When sailing without cargo, the ballast tanks are filled with seawater; when sailing with cargo, they are not filled. Elliptical doubling plates were prepared, as shown in Figure *23*: CRS vs Conventional Steel Investigation, and installed on the upper decks of Nos. 3WBT and No. 5WBT to simulate the progression of coating degradation from coating defect parts (progression of rust and blistering of coating film by rust). (Shiotani & Nakamura, 2015, p. 8.)

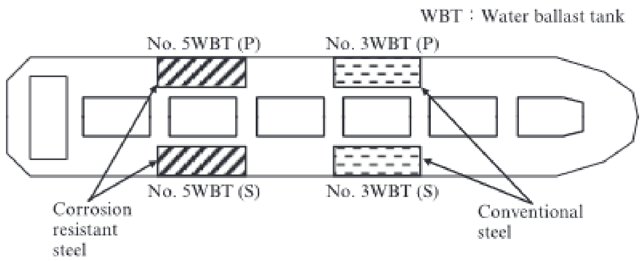

Figure 23: CRS vs Conventional Steel Investigation (Shiotani & Nakamura, 2015)

The typical appearance of coating deterioration is depicted in Figure 26, along with the coating deterioration area at the wide scratches on the doubling plates. The average value of the coating deterioration area of the corrosion resistant steel was 75% that of the conventional steel, even though corrosion and coating deterioration in the form of coating film blistering by rust occurred at the scratched parts. It should be mentioned that, in comparison to the wide scratches, the coating degradation area at the narrow scratches was only reduced by roughly 5%. The corrosion depth of the corrosion-resistant steel was approximately 1.5 mm, or 84% that of the conventional steel, while the corrosion depth of the wide scratches in the conventional steel showed an average value of approximately 1.8 mm. (Shiotani & Nakamura, 2015, p. 10.)

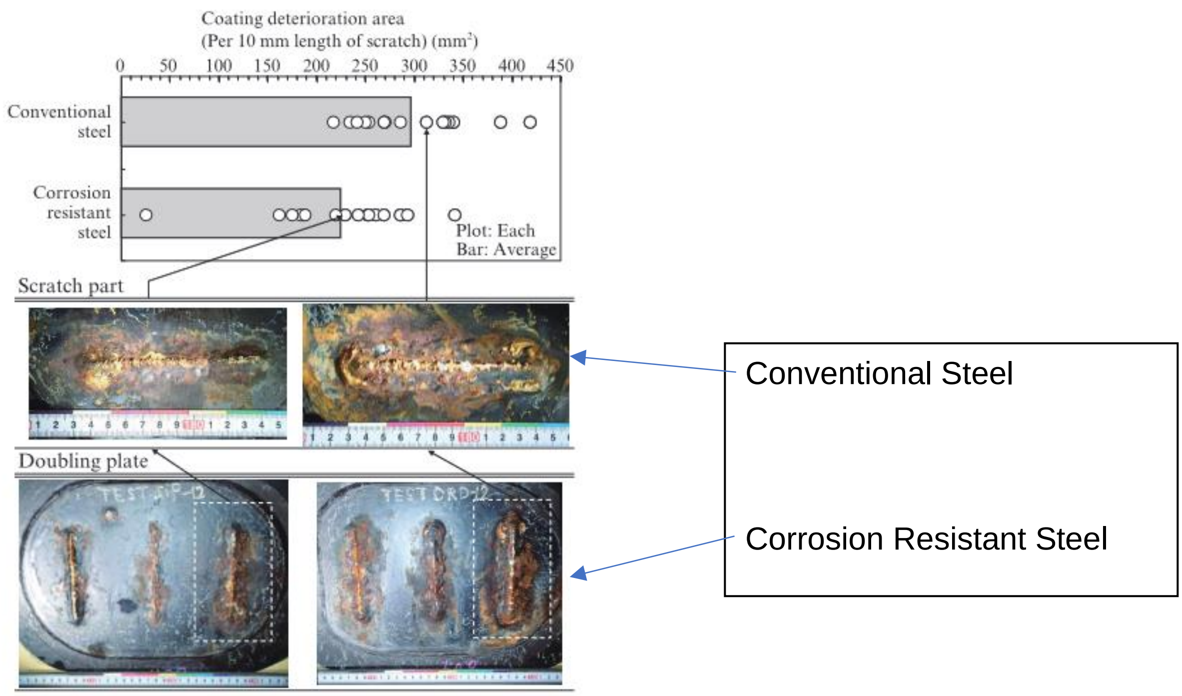

Figure 24: Results after 5 years. (Shiotani & Nakamura, 2015)

The corrosion resistance steel showed remarkably slight corrosion, suggesting that it has a corrosion depth suppressing effect. This type of corrosion was observed over a wide region with the conventional steel test specimen thickness exceeding 3 mm, because of the investigation of corrosion loss of the steel materials in the laboratory corrosion test. Corrosion-resistant steel's corresponding depth in the real test ship was likewise restricted to 84% of that of the conventional steel. This suggests that the corrosion-resistant steel's ability to prevent corrosion loss, as seen in the laboratory corrosion experiment, can also be verified in the real ship. (Shiotani & Nakamura, 2015, p. 15.)

4.9 Type of coating system

Protective Coatings Performance Standard (PSPC) of the IMO

The Performance Standard for Protective Coatings (PSPC) was established by the International Maritime Organization (IMO) to improve the longevity and efficacy of protective coatings applied to seawater ballast tanks on all kinds of ships and bulk carrier double-side skin spaces. The target coating life of PSPC is designed to be at least 15 years ($TSCF_{15}$ equivalent). (TSCF, 2013.)

Tanker Structure Cooperative Forum, or TSCF

For the structural integrity and upkeep of tankers, including matters pertaining to coating systems and corrosion prevention, the Tanker Structure Co-operative Forum offers guidelines and best practices. Although TSCF offers extensive guidelines for coatings and tanker construction and maintenance, its scope is wider, addressing a variety of structural and operational factors for tanker efficiency and safety. Different levels of standards are provided by TSCF for minimum target coating lives of 10, 15, and 25 years (referred to as $TSCF_{10}$, $TSCF_{15}$, and $TSCF_{25}$). (TSCF, 2013, p. 5.)

Highlights of the Comparison

TSCF offers more general guidelines covering corrosion protection and coatings, IMO PSPC is specifically focused on enhancing the longevity and efficacy of ballast tank coatings with precise requirements. While TSCF guidelines act as best practices and recommendations to support the industry in maintaining tanker structural integrity and safety, IMO PSPC is mandatory for international shipping. (TSCF, 2013, p. 9.)

4.9.1 Thickness

For flat surfaces with a nominal total dry film thickness (NDFT) of 320µm, a coating system should generally include at least two spray coats of light-coloured epoxy coating, with 90% of all thickness measurements exceeding or equal to the NDFT and none of the remaining measurements falling below 0.9 x NDFT (also known as the "90/10 rule"). The $PSPC_{15}$ rule's value of 320µm is purportedly misinterpreted as a standard for coating application on flat surfaces, which could ultimately result in non-compliance with the rule as the coating thickness would vary and violate the 90/10 rule.

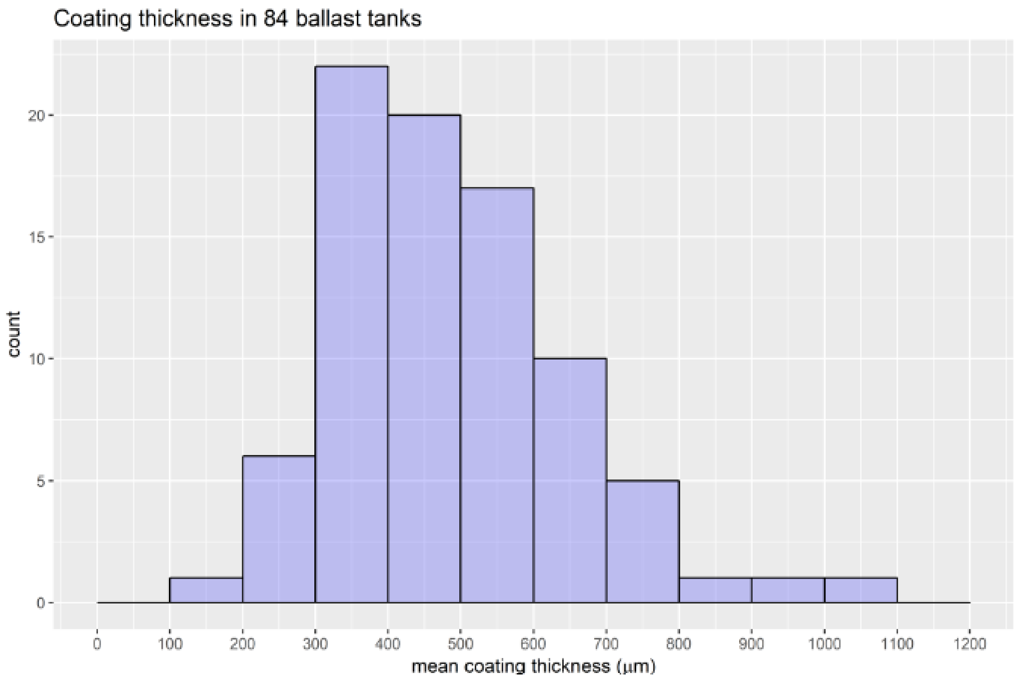

Diagram 2: Average thickness measured. (Willemen et al., 2020)

The coating thickness is 498±18 Pm on average. A significant variation in coating thickness between ships is indicated by the standard deviation of 162μm indicates. The lowest recorded average coating thickness, at 115μm, is significantly less than the 288μm lower bound of $PSPC_{15}$. 1100 Pm is the largest average coating thickness that has been recorded. Between 301 and 600 Pm make up 70% of the thicknesses that have been observed. Furthermore, it seems that the coating thickness has a positively skewed distribution. The possibility of DFT measurements below 288 μm is implied by using 320μm as a benchmark, which carries a risk of a notable deviation in performance from the theoretically average performing coating. It is crucial to understand the $PSPC_{15}$ requirements correctly and avoid using the 320μm as a benchmark. It is important to note that the $PSPC_{15}$ requirement describes the paint system framework; it does not specify the target coating thickness of the paint applicator. (Willemen et al., 2020.)

4.9.2 Paint Quality

Ballast tank coatings are primarily made of light-coloured pure epoxy resin paint and modified epoxy paint. The IMO has mandated light-coloured, hard coatings for ballast tanks in order to facilitate the construction and inspection processes (IMO, Resolution MSC 215(82), 2006). These coatings not only protect against corrosion, but also comply with IMO regulations. During inspections, the light colour makes the tanks easier to see inside and helps identify possible problems like corrosion or contamination. In addition, the paint's hardness guarantees resistance to the challenging marine environment, extending the ballast tanks' useful life and enhancing the overall safety and integrity of the vessel. To guarantee regulatory compliance and optimize these coatings' long-term protective effects, proper application and upkeep are crucial (Coatings, 2016).

4.10 Anodes

Given its benefits, both financially and technically, aluminium anodes are typically chosen over zinc anodes. However, because there's a chance of sparking if the anodes fall off, there are issues with using aluminium alloyed anodes in some tanks.

An aluminium anode may produce a thermite spark if it meets a rusty surface. As a result, its application is limited to tanks with potentially explosive environments and anode drop hazards. The following situations are when the restrictions are in effect:

- Liquid cargo tanks with a flash point of less than 60°C.
- Beside tanks for liquid cargo with a flash point of less than 60°C are ballast tanks.

Sacrificial anodes in tanks must consider the following factors in compliance with DNV-CG-0288 Corrosion protection for ships:

- Materials for anode alloys based on zinc or aluminium are acceptable. Alloys based on magnesium are unacceptable.

- It is necessary to place aluminium anodes such that, in the unlikely event that they come loose and fall, a kinetic energy of less than 275 J is developed.
- A 10 kg aluminium anode needs to be placed lower than 2.8 m from the tank bottom based on elevation vs weight. (Perez, 2004.)

4.11 Cost

Project managers, constructor and investors can use the cost analysis as a starting point to investigate the lifetime cost construction of ballast tanks in comparative with different protective methods. Assessing the possible financial benefits of longer maintenance intervals, fewer repairs needed, and increased vessel safety and compliance are some of the possible outcomes of this inquiry. Furthermore, comparing studies with newer technologies and alternative coating options can provide information on how to maximize cost-effectiveness while still fulfilling performance requirements and regulatory standards. (W.D Callister, 2006.)

4.11.1 Total cost of Ballast Tanks

When the ship is sold for scrap, the residual value is subtracted from the initial investment plus operating costs for a 25-year period, and the DR is used as the discount rate. This results in the TCB (Total cost of ballast tanks) as shown in $TCB = Initial\ Investment + \sum_1^{25} \frac{Exploitation\ cost}{(1+DR)^n} - \frac{Residual\ value}{(1+DR)^n}$...........Equation 1. (Fahad & Rana, 2017.)$TCB = Initial\ Investment + \sum_1^{25} \frac{Exploitation\ cost}{(1+DR)^n} - \frac{Residual\ value}{(1+DR)^n}$...........Equation 1

$TCB = Initial\ Investment + \sum_1^{25} \frac{Exploitation\ cost}{(1+DR)^n} - \frac{Residual\ value}{(1+DR)^n}$...........*Equation 1*

4.11.2 Calculations of Initial Investment

It is possible to compute the initial investment for each of the cases as follows:

$Initail\ Investment = Steel\ cost + Coating\ cost + Anode\ cost$ ………………………………… *Equation 2*

$Steel\ cost = Lightweight \times\ Cost\ of\ steel$ ……………………………………………………….*Equation 3*

$Lightwight = Surface\ Area\ \times Thickness\ \times Density$ ……………………………………………*Equation 4*

$Coating\ cost = Surface\ Area\ \times Initial\ coating\ per\ m^2$ ………………………………………. *Equation 5*

$Anode\ Cost = Number\ of\ Anodes\ \times Initial\ Installation\ cost\ per\ anode$ ……………………. *Equation 6*

4.12 Cost of exploitation

Project managers are able to make well-informed decisions about corrosion prevention measures, budget allocations, and maintenance schedules by thoroughly analysing different factors. Ship operators can maximise returns on investment by prioritising investments in areas that prolong the service life of ballast tanks and reduce operational disruptions by accurately assessing exploitation costs. The long-term viability of vessel operations is further ensured by continual monitoring and assessment of exploitation costs, which permits ongoing improvement in maintenance procedures and cost-management techniques. (W.D Callister, 2006.)

4.13 Value residual

The ship is sold for the scrap iron value after 25 years of service. The higher concentrations of valuable alloys are unlikely to affect the scrapping price, so the tanks built in CRS (case IV) can also be valued at the same amount. Next, residual value can be computed using the formula below:

$Value\ of\ Residual = Lightweight\ \times Value\ of\ the\ Scrap\ Iron$ …………………………………*Equation 7*

4.14 Discussion

The most popular method for reducing tank corrosion is coating, this method protects the steel against corrosive substances. Paints based on epoxy that are applied and maintained properly can last up to 15 years. Anodes Normally, ballast tanks are equipped with sacrificial anodes. These can offer protection against corrosion in areas where coating damage or localized coating breakdown takes place. Based on the research and general knowledge the increased scantling technique in case II can be categorized as economically unhealthy. Expanded scantlings provide sufficient corrosion protection, but the cost of increased lightweight and resulting loss of cargo carrying capacity is just too great. This conclusion supports J. Eliasson's (2003), claim that it is possible to construct ships out of thick enough steel to maintain enough strength throughout free corrosion and still fulfil the intended service life, but that this is no longer a financially viable method of building and managing ships. In general, anything good is very expensive for example the Corrosion resistant steel is more expensive than the grade A steel used but it’s the best material for ballast construction if their available finance, then using CRS case IV becomes more appealing. Case I represent the most common method for ballast tanks construction and this method is not the worst option, however there’s plenty room for improvement.

A logical progression from case I is case V. To make the weight last the ship's entire economic life, aluminium anodes have been used in place of the sacrificial Zn anodes. Zinc is regarded as the traditional anode material since it has been used as a sacrificial anode for a longer period than aluminium. Nonetheless, aluminium is quickly taking the lead due to its many exceptional benefits as a sacrificial anode material. However, aluminium can not be used in vessel transporting liquid cargo with a flash point less than 60 degress.

4.15 Recommendation

In the thesis, various corrosion protection techniques for ballast tanks such as coatings and cathodic protection etc. that led the marine industry's efforts to improve vessel durability against challenging marine environments were carefully compared. However, corrosion itself is a complex study area and requires more time and lots of laboratory experiments to get the best findings in the different materials used in the protection against corrosion for the construction of the ballast tanks. After finding the best methods, test trails should be carried to determine if the selected methods or strategies are really the best. Otherwise at least real time simulations software programs should be used with speed time functions or by constructing them in already in use vessel around the 7 seas to get the best suitable results.

4.16 Conclusion

Currently, the best method for protecting ballast tanks is to apply a standard PSPC 15 coating under ideal application conditions on a substrate that has been meticulously prepared. If the lifetime aluminium anodes are evenly spaced throughout the ballast tank and are kept up with, they can then be utilized as a backup system. Furthermore, the creation of a better paint system with greater resistance to impact damage appears to be the most promising area of study.

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