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Research Paper

Analysis of Corrosion Rate and Surface Changes on Zinc Anodes in The Hull Ship

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Abstract

As a vast maritime nation, Indonesia relies heavily on sea transportation, where ships play a critical and indispensable role in maintaining inter-island connectivity and supporting national economic development. However, prolonged exposure of a ship's hull to the harsh marine environment makes the material highly susceptible to electrochemical corrosion. This degradation can significantly compromise the vessel's structural integrity, increase maintenance costs, and threaten operational safety at sea. One of the most effective and widely implemented corrosion protection techniques in the maritime industry is the galvanic cathodic protection system using sacrificial anodes, with zinc (Zn) being a frequently utilized material due to its favorable driving voltage and reliability in seawater. This study specifically investigates and analyzes the corrosion rate and surface morphology changes of zinc anodes installed on various sections of a 1200 DWT Ro-Ro vessel over a comprehensive one-year monitoring period. The research employed weight-loss measurements to determine the precise corrosion rate, while the microstructural surface morphology and elemental composition were analyzed in detail using Scanning Electron Microscopy (SEM) and Energy Dispersive X-Ray Spectroscopy (EDS). The empirical results and data analysis indicate a significant variation in corrosion rates depending on the anode's placement. The highest corrosion rate was observed on the anodes at the vessel's stern, reaching 2.6 mpy, whereas the lowest rate was recorded in the mid-hull section at 0.254 mpy. This disparity is primarily attributed to the complex hydrodynamic conditions around the hull; specifically, the high water turbulence and increased dissolved oxygen concentration near the stern caused by continuous propeller rotation accelerate the anodic dissolution process. Further compositional analysis revealed that aluminum oxide (Al2O3) was the dominant corrosion product, accounting for approximately 46.74% of the total anode material content. SEM observations identified localized pitting and cavity corrosion patterns; nevertheless, more than 50% of the overall anode surface remained electrochemically active and intact after one year of installation. These findings provide essential practical insights for naval architects and ship owners in predicting anode service life, planning material replacement, and optimizing maintenance schedules for marine cathodic protection systems. Future research is recommended to explore the synergistic influence of other environmental parameters, such as salinity, seawater temperature, and vessel operational speed, on the long-term performance of sacrificial anodes.

Keywords: *Zinc anode, Corrosion rate, Ship hull, Cathodic protection, Weight loss*

INTRODUCTION

As an archipelagic nation with roughly 62% of its territory comprising ocean, Indonesia occupies a pivotal strategic position in global maritime affairs. Its exceptionally extensive coastline, stretching over 99,000 km, and its constellation of thousands of islands fundamentally dictate that sea transportation serves as the indispensable backbone of national connectivity, logistics, and economic distribution. Consequently, ships are far more than mere vehicles for inter-island transport; they are vital, dynamic components of critical infrastructure that actively drive economic growth, facilitate trade, and enable socio-economic integration across the sprawling nation. The reliability and safety of this maritime fleet are, therefore, paramount to national

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stability and prosperity (Sui et al., 2020; Sultan et al., 2023; Amin et al., 2021). Ships operate in seawater environments with high salinity, which are inherently corrosive. The most vulnerable part of a ship is its hull, as it is in constant and direct contact with seawater. This continuous exposure subjects the hull material to aggressive electrochemical and chemical processes, leading to inevitable degradation. Protecting the hull from corrosion is therefore a fundamental engineering challenge, critical for ensuring the vessel's structural integrity, operational safety, and economic lifespan. Effective corrosion mitigation is essential for maritime safety and asset preservation (Ji et al., 2024; Starosta, 2019). Hull corrosion represents a paramount maintenance challenge in the maritime industry. This relentless process directly leads to the thinning of structural materials, compromising the vessel's integrity, and can precipitate significant structural damage. These effects ultimately pose grave and direct risks to operational safety, potentially leading to catastrophic failures. Beyond safety, corrosion also degrades hydrodynamic efficiency, increasing fuel consumption and operational costs, while the release of corrosion byproducts and compromised anti-fouling coatings can create environmental hazards. Therefore, implementing and maintaining a robust corrosion protection system transcends routine upkeep; it is a critical, non-negotiable aspect of responsible vessel management. It is fundamental to safeguarding the ship's structural integrity, ensuring the absolute safety of the crew and cargo, and preserving the asset's significant long-term economic value. Proactive, science-based corrosion mitigation strategies are not merely beneficial but are essential for ensuring safe, efficient, and sustainable maritime operations (Ivošević & Kovač, 2023; Vu & Dong, 2021).

Several methods have been developed to mitigate hull corrosion, including protective coatings (painting), design modifications, environmental control, and electrochemical protection. Among these, one of the most widely implemented electrochemical techniques is the use of sacrificial anodes, such as zinc anodes. These anodes are strategically attached to the ship's hull, where they are intentionally sacrificed, corroding preferentially to protect the underlying, more critical hull material. This fundamental electrochemical process, known as cathodic protection, operates on the principle of making the steel hull the cathode of a deliberately created corrosion cell. By connecting it to a more electrochemically active metal, such as the sacrificial zinc anode, the entire system's corrosion potential shifts. This effectively redirects the corrosive attack away from the critical steel structure, forcing the oxidation reaction (the loss of metal) to occur almost exclusively on the sacrificial anode instead. As the anode corrodes, it releases electrons that flow to the hull, halting its corrosion. This mechanism significantly extends the vessel's service life by preventing structural thinning, fatigue, and failure, while also maintaining hydrodynamic efficiency and reducing long-term repair costs. The widespread global adoption of zinc anodes across the maritime industry is a direct result of their proven effectiveness, operational reliability, and outstanding cost-efficiency in preserving valuable maritime assets. Zinc offers an optimal balance: it possesses a suitably negative electrochemical potential to robustly protect steel, corrodes in a relatively uniform and predictable manner, and is abundantly available, making it an economically viable solution for both large commercial fleets and smaller vessels. This combination of reliable performance and economic practicality has solidified its role as a cornerstone technology in marine asset preservation (Srivastava et al., 2024; Xu et al., 2021; Nwanonenyi et al., 2025).

This study aims to comprehensively analyze the corrosion rate of zinc sacrificial anodes installed at various critical positions, specifically the bow, midship, and stern, on the hull of a 1200 DWT Ro-Ro vessel. The research seeks to quantify and compare the degradation experienced in these distinct hydrodynamic and operational environments over a standard service period. In addition to measuring corrosion rates, this investigation meticulously examines changes in the anodes' surface characteristics and fundamental material properties resulting from 1 year of continuous marine exposure. This methodology employs a dual approach, integrating precise quantitative weight-loss analysis with advanced microscopic examination, such as Scanning Electron Microscopy (SEM), to meticulously document physical degradation and compositional changes in the anodes. Ultimately, the empirical findings from this comprehensive work are expected to yield actionable, practical insights for the maritime industry. These data-driven results aim to inform and optimize maintenance strategies, enabling more accurate scheduling and cost-effective management of cathodic protection systems on vessels. The data will support the establishment of more scientifically informed, effective, and cost-efficient replacement schedules for sacrificial anodes, thereby enhancing the reliability of corrosion protection systems and improving vessel lifecycle management (Anwar et al., 2025).

LITERATURE REVIEW

Although sacrificial zinc anodes are highly effective and reliable for cathodic protection, they have a finite service life and require periodic replacement to maintain their protective function. A significant practical challenge in their maintenance is the difficulty of performing direct, accurate visual inspections because they are permanently submerged on the vessel's hull. Moreover, while their use is widespread, there has been a notable lack of detailed, quantitative, and position-specific field assessments of their actual corrosion rates under real operational conditions. This gap in empirical data underscores the critical need to systematically analyze and accurately predict the degradation behavior of these anodes. By establishing precise corrosion rate data, the maritime industry can move from calendar-based to condition-based maintenance. Such a data-driven approach is essential for developing optimized, cost-effective maintenance and replacement schedules. This optimized strategy ensures resources are allocated with maximum efficiency. It directly prevents two major pitfalls: the unnecessary cost of premature anode replacements and the severe risk of protective system failure caused by overdue anodes. Consequently, it safeguards the vessel's structural integrity, creating a balance between safety, reliability, and cost-effectiveness (Nwanonenyi et al., 2025; Tamhane et al., 2021).

RESEARCH METHOD

Location and Time of Research

This research was conducted at Tanjung Emas Port in Semarang, Indonesia, utilizing a 1200 DWT Roll-on/Roll-off (Ro-Ro) vessel as the primary subject during its scheduled dry-docking maintenance period. The selection of this major commercial port as the study site was deliberate, based on its significant maritime traffic and representative environmental conditions typical of tropical Indonesian waters. Factors such as salinity levels, water temperature fluctuations, and biological activity at this location provide a realistic and highly relevant setting for assessing marine corrosion. Conducting the study during the vessel's mandatory dry-docking period provided a critical, invaluable opportunity for precise, safe, and undisturbed access to the hull and its installed sacrificial anodes. This controlled access was fundamental to the research methodology, as it enabled the team to perform highly accurate initial dimensional and weight measurements of the anodes in their post-service state. More importantly, it enabled the systematic and careful retrieval of anode samples from their exact positions on the bow, midship, and stern. These samples were then preserved and transported for subsequent detailed laboratory analysis, including advanced techniques such as Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS). This phase of the work, bridging field observation with laboratory science, is crucial for understanding the microstructural and compositional changes induced by corrosion. By anchoring the investigation in this real-world, operational context, yet within the controlled conditions of a dry dock, the study ensures that the collected quantitative data on anode degradation rates and patterns are not only scientifically rigorous and reproducible but also highly externally valid.

Consequently, the findings are directly applicable and highly relevant to the practical, real-world operational scenarios, maintenance challenges, and economic decisions faced by ship operators and managers across the regional and global shipping industry, translating academic insight into actionable engineering intelligence.

The comprehensive data collection and systematic observation regimen for this study was meticulously designed to span a full, continuous one-year operational cycle, from January 2024 to January 2025. This specific 12-month duration was strategically chosen to comprehensively capture the effects of seasonal environmental variations on corrosion processes. The tropical maritime climate of Semarang experiences distinct seasonal shifts, including monsoon-driven changes in wave action and water turbidity, as well as cyclical variations in sea surface temperature and salinity. These fluctuating parameters are known to significantly influence electrochemical corrosion rates. By monitoring the anodes across all seasons, the research aims to isolate and understand these environmental impacts, moving beyond a simple average to a dynamic model of degradation. The primary and fundamental focus of this scientific inquiry is to accurately determine, quantify, and analyze the in-situ corrosion rate of zinc sacrificial anodes under these realistic and varying conditions. This involves not just calculating a single annual rate but potentially identifying periods of accelerated or decelerated corrosion linked to specific environmental factors, thereby providing a nuanced and highly practical understanding of anode performance throughout the year.

These anodes were strategically installed at three distinct and critically important locations on the ship's hull, which are subjected to varying hydrodynamic and operational stresses: namely, the bow, the midship, and the stern sections. Each location presents a unique microenvironment; the bow faces constant water impact and air entrapment, the midship experiences relatively stable flow, and the stern is subjected to intense turbulence, cavitation, and oxygen-rich water from propeller action, all of which are hypothesized to significantly influence the anode's degradation rate. This positional analysis is crucial for understanding localized corrosion dynamics and developing a holistic view of the protective system's performance. By comparing degradation at the bow, midship, and stern, the study identifies how hydrodynamic forces, oxygen concentration, and mechanical stress create distinct micro-environments that accelerate or slow corrosion. This detailed mapping across the entire hull structure reveals weaknesses, informs optimal anode placement, and enables the creation of a more accurate, predictive model for the system's performance over an extended operational timeline, ensuring reliable long-term protection (The American Bureau of Shipping 2018; Gosselin et al., 2025).

Data collection

Data collection for this study was executed through a multi-method approach, employing several complementary techniques to ensure comprehensive and triangulated findings. First, structured and semi-structured interviews were systematically carried out with key informants, including deck crew members (ABK – Anak Buah Kapal), engineering officers, and port maintenance personnel. These interviews aimed to obtain rich qualitative data regarding operational experiences (Matusalem et al., 2024), maintenance practices, and the perceived impact of hull corrosion on vessel performance and safety (Pulukadang, 2025). Second, direct field observation and documentation were rigorously performed. This involved assessing the physicochemical water conditions, including clarity, pollution indicators, and biological activity, in the study area around Tanjung Emas Port. Simultaneously, detailed visual and tactile inspections were conducted to document the physical condition of the zinc anodes on the vessel's hull, noting surface morphology, fouling, and visible wear patterns before and after the service period. In addition, an extensive literature review was undertaken to gather and synthesize foundational theoretical references and established empirical data (Pulukadang, 2025). This review focused on core principles of marine electrochemistry, standardized methods for corrosion rate analysis (e.g., ASTM standards), and the fundamental mechanical properties and degradation pathways of shipbuilding steel materials. Integrating these qualitative insights, direct observational data, and established theory provided a robust framework for analyzing the empirical corrosion measurements.

Test Equipment

The experimental analysis in this study utilized specific equipment to obtain precise quantitative and qualitative data on the corrosion process. To characterize the corrosive marine environment, a calibrated salinometer was employed to accurately measure the salinity of seawater samples. These samples were collected from the vessel's operational environment and analyzed under controlled conditions at the Maritime University AMNI Semarang laboratory, establishing a key environmental parameter. For the detailed examination of the anode material itself, advanced imaging and analytical instruments were crucial. Scanning Electron Microscope (SEM) instruments were used to perform high-resolution analysis of the surface morphology of the zinc anodes retrieved after one year of operational use. This technique revealed critical microstructural features such as pitting, grain boundary attack, erosion patterns, and the distribution of corrosion products. The foundational metric of the investigation, the corrosion rate, was primarily determined using the standardized weight-loss method. This involved precise measurement of the mass reduction of the anode samples, which was then calculated using a standard formula that factors in the material density, exposed surface area, and exposure time to yield a rate in mils per year (mpy). The integration of environmental data (salinity), microscopic surface analysis (SEM), and the fundamental weight-loss calculation provided a multi-faceted understanding of the degradation mechanisms and their kinetics.

The corrosion rate was quantitatively determined using the standardized weight loss method, a fundamental technique in corrosion science. The rate is calculated and expressed through the following established and widely accepted formula, which relates mass loss to material density, surface area, and exposure time (Taofeek et al., 2024; Budiyanto, 2024).

$$MPY = ((534 \times \mathrm{W})))/(/(\mathrm{D} \times \mathrm{A} \times \mathrm{T}) \qquad (1)$$

Where:

MPY = Corrosion rate (mils per year)
W = Weight loss due to corrosion (mg)
D = Density of the material (g/cm^3)
A = Exposed surface area (in^2)
T = Exposure time (hours

The research procedure followed a structured, sequential methodology. It was initiated with a comprehensive preliminary study and literature review to establish the theoretical framework. This was followed by the controlled installation of new zinc anode specimens at predetermined locations on the vessel's hull. After a full year of in-situ marine exposure, the specimens were carefully retrieved during dry-docking. Each anode was then meticulously cleaned, dried, and weighed to determine the precise mass loss. This quantitative data served as the direct input for calculating the corrosion rate using the standard formula. Subsequent stages involved systematic data analysis, interpretation of the results in the context of positional and environmental variables, and the synthesis of all findings into a conclusive final report.

FINDINGS AND DISCUSSION

Researchers collected and generated data through a series of controlled laboratory tests. These included measuring seawater salinity with a salinometer, determining anode mass loss for corrosion rate calculation, and conducting high-resolution surface analysis using Scanning Electron Microscopy (SEM) to examine morphology and elemental composition.

Corrosion rate

The corrosion rate was calculated using the weight loss method. This involved precisely measuring the mass of the zinc anodes both before installation and after retrieval from the ship's hull following 1 year of operational exposure in seawater. The results of the weight-loss analysis revealed significant, systematic variations in corrosion rate that were directly dependent on the anode's position on the vessel's hull. For the Bow Anode, exposed to constant water impact and potential air-bubble impingement, the corrosion rate was measured at 1.6 Mpy (mils per year). In contrast, the Midship Anodes (both starboard and port), which operate in a region of relatively stable, streamlined water flow with less turbulence, exhibited the lowest degradation, with a corrosion rate of just 0.254 Mpy. Most notably, the Stern Anode demonstrated the most aggressive degradation, with the highest observed corrosion rate reaching 2.6 Mpy. This pronounced acceleration is conclusively attributed to the extreme hydrodynamic conditions at the stern, characterized by intense turbulence, cavitation, and oxygen entrainment induced by the propeller's rotation, which dramatically enhance electrochemical corrosion activity at the anode surface. These positional findings are critical for predictive maintenance modeling. These significant positional differences in the measured corrosion rates from 0.254 Mpy at midship to 2.6 Mpy at the stern are clearly illustrated and can be further analyzed using the following comparative graph.

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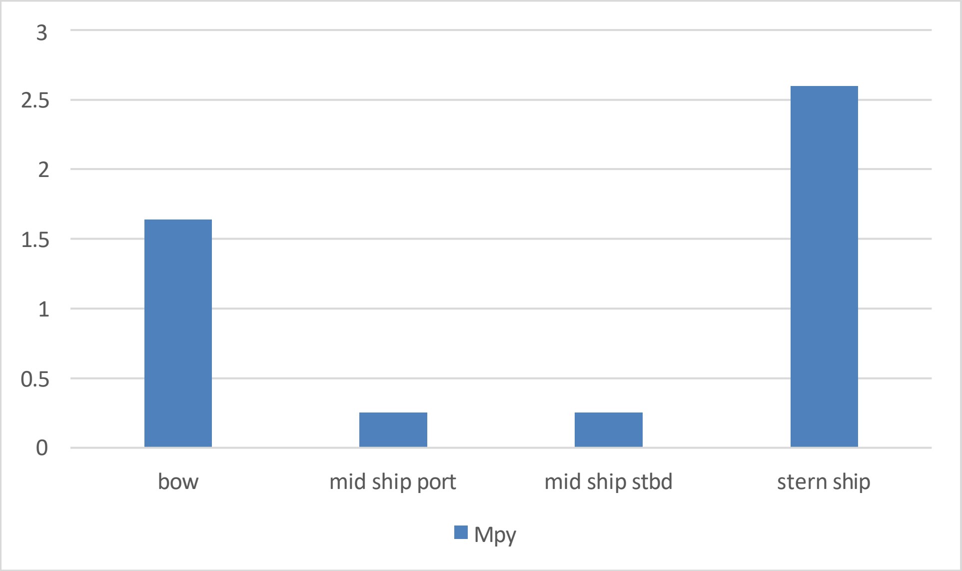

Figure 1. Corrosion Rate Anoda

From the graph above, which shows corrosion rate (mpy) by anode position, it is clear that the highest corrosion rate occurs at the vessel's stern (2.6 Mpy), well above the moderate bow rate (1.6 Mpy) and the low midship value (0.254 Mpy). This underscores the direct link between the intense hydrodynamic conditions at the propeller-driven stern and the rapid degradation of the sacrificial anode. The stern's harsh environment, marked by turbulence and propeller cavitation, increases local dissolved oxygen levels, accelerating the cathodic reaction and accelerating anode corrosion. As a result, the stern anode deteriorates much faster than those in calmer areas. In contrast, the midship section's laminar flow and lower oxygen replenishment limit corrosion, resulting in much lower degradation rates.

Metal Composition and Surface Condition Analysis

The metal composition analysis of the retrieved zinc anodes, conducted after one full year of marine exposure, was performed at the Integrated Laboratory of Diponegoro University to determine their precise elemental makeup post-corrosion. Using advanced analytical techniques such as Energy-Dispersive X-ray Spectroscopy (EDS) coupled with Scanning Electron Microscopy (SEM), the test results provided critical insights into the anode's degraded state. The analysis revealed that the dominant chemical component present on and within the anode material was aluminum oxide (Al_2O_3), which constituted a significant 46.74% of the analyzed composition. This high percentage of an oxide compound is a direct indicator of the extensive oxidation processes that occurred during service. It signifies that the sacrificial zinc has not only lost mass but has also undergone a fundamental chemical transformation, converting into stable oxide and other corrosion products. The presence and proportion of Al_2O_3 are particularly important as they influence the anode's residual conductivity, the structure of the corrosion product layer (which can sometimes be protective or non-protective), and ultimately, its remaining efficacy and lifespan in the cathodic protection circuit. This specific chemical composition, dominated by aluminum oxide (Al_2O_3), serves as direct empirical evidence of the anode's primary function and operational mechanism: the protection of the ship's hull through active, sacrificial corrosion. The high oxide content, particularly of elements more active than steel, confirms that the zinc-based material has preferentially undergone oxidation over the extended service period. In this electrochemical process, the anode deliberately corrodes sacrificing itself by releasing electrons. These electrons are then supplied to the steel hull, cathodically polarizing it and thereby halting its own corrosion reaction. The formation of Al_2O_3 and other compounds represents the spent byproducts of this essential protective action, where the anode material is consumed to safeguard the underlying and more critical steel structure. Conversely, the component found with the lowest concentration was potassium oxide (K_2O), recorded at a minimal 0.33%. This trace amount likely originates from impurities within the original anode alloy or, more plausibly, from deposits and inclusions from the seawater electrolyte itself, such as salts or biological matter, that adhered to the anode's highly reactive and porous corroded surface during its year-long immersion. Its negligible percentage confirms it plays no significant role in the core sacrificial protection process.

Tabel 1. Results of Metal Composition Analysis

No	Speciment	Paramater	Measurement	Analytical results	Method	Remaks
	Zinch Anode	C	% Weight	34,23	SEM EDX	
		Na_2O		1,78		
		MgO		1,06		
		Al_2O_3		46,74		
		SiO2		0,67		
		K_2O		0,33		

No	Speciment	Paramater	Measurement	Analytical results	Method	Remaks
		CaO		1,80		
		FeO		3,17		
		ZnO		10,22		

To conduct a detailed examination of the surface morphology of the zinc anodes following one year of corrosion exposure, high-resolution Scanning Electron Microscopy (SEM) was performed. This advanced imaging technique was employed at progressively higher magnifications, extending up to 20,000X, to capture both macro-scale features and microstructural details of the degraded surfaces. The resulting SEM micrographs provided unambiguous visual evidence, revealing distinct irregular pits and cavities across the anode material. These pits varied in depth and diameter, and their distribution corresponded with areas of greatest material loss. These specific morphological alterations, namely pitting and cavity formation, are classic and direct visual indicators of active sacrificial corrosion. They serve as empirical proof that the anodes had performed their intended function correctly. The micrographs illustrate the process by which the sacrificial zinc material preferentially and systematically underwent electrochemical degradation, dissolving at the anode sites to generate a protective current. This cathodic polarization of the adjacent steel hull successfully inhibited its corrosion. The observed pitting is the physical manifestation of this protective sacrifice, confirming the anode's consumption was both active and localized, directly corresponding to the protection of specific areas of the ship's hull over the operational period.

Figure 2. SEM Test Results

Despite the clear presence of localized corrosion features such as pits and cavities, a comprehensive visual inspection of the high-resolution SEM images indicated a significant portion of the anode material remained preserved. Analysis of the micrographs revealed that more than 50% of the total anode surface area remained structurally intact and uncorroded. These areas were characterized by brighter, more reflective regions and distinct, elevated structures in the SEM topography, which correspond directly to the original alloy's microstructure that had not yet undergone significant electrochemical dissolution. This key observation is crucial, as it confirms that the zinc anodes retain considerable residual protection capacity even after completing a full year of harsh marine service. The presence of this substantial uncorroded volume signifies that the anodes have not been exhausted. They continue to possess ample sacrificial material capable of generating the necessary protective current, suggesting their effective service life extends beyond the one-year mark. This finding has direct and significant practical implications for vessel maintenance planning and operational budgeting. The data indicating that over 50% of the anode material remains intact after one year provides a quantitative basis for moving beyond fixed, calendar-based replacement schedules. It strongly suggests that anode replacement intervals could be potentially optimized and strategically extended based on actual measured degradation rates rather than conservative estimates. By implementing a condition-based maintenance approach informed by such empirical data, ship operators can achieve substantially greater cost efficiency. This optimization reduces material costs, lowers dry-docking labor expenses, and minimizes vessel downtime. Crucially, this is achieved without compromising the integrity of the cathodic protection system or the vessel's hull safety. The approach ensures that anodes are replaced only when necessary, maximizing their usable service life while continuously maintaining the required protective current, thereby striking an optimal balance between economic management and unwavering operational safety.

CONCLUSIONS

The corrosion rate of zinc sacrificial anodes used for the cathodic protection of ship hulls is a critical parameter that is highly and demonstrably influenced by their specific installation location on the vessel's structure. This research, conducted on a 1200 DWT Ro-Ro vessel over a one-year operational period, provided conclusive evidence of this positional dependency. The most aggressive degradation was observed at the stern, where anodes recorded the highest average corrosion rate of 2.6 mils per year (Mpy). This stands in stark contrast to the conditions at the midship, where anodes experienced the most benign environment, resulting in the lowest measured corrosion rate of only 0.254 Mpy. The bow section presented an intermediate condition, with a corrosion rate of 1.6 Mpy. These disparities are not random but are directly attributable to the distinct hydrodynamic and electrochemical microenvironments at each location. The stern is subjected to intense turbulence, cavitation, and aeration caused by propeller action, which dramatically increases the supply of dissolved oxygen, a key reactant in the cathodic process, thereby accelerating the sacrificial corrosion of the anode. The midship, benefiting from more laminar flow and lower oxygen replenishment, experiences a much slower, diffusion-controlled corrosion process.

Post-service material analysis revealed critical insights into the anode's composition and degradation mechanism. Through detailed laboratory examination, the main metallic component identified in the corroded zinc anodes was Al_2O_3 (aluminum oxide), accounting for 46.74% of the analyzed material. This high concentration of oxide is a direct chemical testament to the anode's operational success; it confirms that the material has actively undergone oxidation, effectively contributing to the anode’s sacrificial protection behavior by corroding preferentially to protect the underlying steel hull. The formation of this stable oxide layer is part of the expected degradation pathway. Furthermore, analysis of surface morphology via Scanning Electron Microscopy (SEM) provided visual confirmation of the quantitative data. After 1 year of continuous marine service, the anode surfaces exhibited clear, noticeable corrosion features, including irregular pits and cavities characteristic of localized sacrificial dissolution. However, a pivotal finding was that more than 50% of the total surface area remained intact. These uncorroded regions, appearing as brighter, elevated structures in SEM images, represent a substantial reserve of unreacted zinc material. This indicates that the anodes retain significant residual protective capacity and have not been exhausted.

The practical implications of these combined findings are substantial. Firstly, the relatively low absolute corrosion rate, even at the most aggressive location (the stern), strongly suggests that the service life of these zinc anodes under the studied conditions exceeds 1 year. This challenges generic or overly conservative replacement schedules. Therefore, these empirical findings provide a robust scientific basis for ship operators and maintenance planners to transition from standardized periodic replacements to data-driven, optimized maintenance strategies. Based on the quantified degradation rates and residual material analysis, a specific operational recommendation can be formulated. It is advised that ship operators consider implementing a staged or zonal replacement strategy within a proposed two-year maintenance cycle. This strategy would prioritize replacing anodes in the highest-demand area first. Specifically, stern anodes, having endured the highest corrosion rate, should be replaced at the end of the first year or during the first scheduled dry-dock within the cycle. The bow anodes, with a moderate corrosion rate, could be inspected and potentially replaced at an 18-month interval or during the same dry-dock as the stern, if logistics permit. Finally, the midship anodes, which corrode at a rate nearly an order of magnitude slower, are likely to remain in service for the full two-year cycle before requiring replacement, given confirmation of over 50% residual material at the one-year mark.

Such a nuanced, location-aware approach directly enhances maintenance cost efficiency by avoiding the premature replacement of still-serviceable anodes (particularly at the midship), reducing material costs, and optimizing labor during dry-docking periods. Crucially, this is achieved without compromising the optimal corrosion protection performance for the ship hull. By aligning replacement schedules with the actual, measured degradation rates for different hull zones, operators can ensure continuous protection while maximizing the economic use of sacrificial anode materials, thereby achieving an optimal balance between operational safety, asset longevity, and fiscal responsibility. This study underscores the value of condition-based monitoring and tailored maintenance planning in maritime asset management.

LIMITATION & FURTHER RESEARCH

The primary limitation of this study lies in its specific scope; the analysis was conducted using zinc anode specimens installed on a single vessel, a class A 1200 DWT Ro-Ro ship, that was corroded under the particular seawater conditions at Tanjung Emas Port. Factors such as specific water chemistry, operational profile, and hull coating integrity can influence results. Therefore, the findings are most directly applicable to similar vessels in comparable environments. To enhance generalizability, further research is strongly recommended. Future studies should investigate and identify the optimal composition and specifications for zinc anode alloys to maximize corrosion protection efficiency and longevity across a broader range of ship types, sizes, and operational routes.

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