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Electrochemical Performance of Sacrificial Anode Metals in Preventing Corrosion on Ships: A Literature Review

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ABSTRACT

Corrosion is a persistent and urgent problem for ships operating in high-salinity seawater environments, as it not only threatens structural integrity but also increases maintenance costs and reduces operational safety. One of the most widely applied methods of corrosion prevention is cathodic protection using sacrificial anodes, yet challenges remain in selecting the most effective and sustainable material. This article presents a literature review on the effectiveness of various metals used as sacrificial anodes, including zinc (Zn), aluminum (Al), and magnesium (Mg). The review highlights that each metal has unique characteristics: zinc offers stable potential and moderate service life, aluminum provides high current capacity with lightweight properties, while magnesium delivers the highest protective potential but corrodes rapidly in seawater. The urgency of this research lies in the growing demand for durable and environmentally friendly solutions for modern maritime fleets, particularly as ships are increasingly deployed in harsher marine environments. Unlike previous studies that mainly focused on performance comparison, this review emphasizes the integration of operational conditions, environmental sustainability, and cost-effectiveness in anode selection. Therefore, this study provides a novel contribution by offering a holistic perspective to guide the maritime industry in designing cathodic protection systems that are not only effective but also aligned with long-term economic and ecological considerations.

INTRODUCTION

Corrosion on ships is an electrochemical degradation process caused by reactions between the metal hull and the marine environment. Seawater, rich in chloride ions (Cl^-), accelerates the oxidation process of carbon steel, the most common ship hull material. Corrosion damage results in structural integrity loss, increased maintenance costs, and potential structural failures, posing significant safety risks.

One effective corrosion prevention technique is cathodic protection, which involves making the protected metal act as the cathode in an electrochemical cell, thereby preventing oxidation. Cathodic protection can be implemented through Impressed Current Cathodic Protection (ICCP) or Sacrificial Anode Cathodic Protection (SACP).

SACP employs a metal with a more negative electrode potential than the protected structure. This sacrificial metal corrodes in place of the ship's hull. Common sacrificial anode materials for marine applications include zinc, aluminum, and magnesium (Sundjono et al., 2017; Wang et al., 2024; Zhang et al., 2021; Zhao et al., 2024; Zhou et al., 2024).

Several studies have examined the effectiveness of sacrificial anodes in mitigating ship corrosion, but many have been limited to either laboratory-based electrochemical performance or single-metal evaluation (Y. Li et al., 2025; Oloruntoba et al., 2024; Shang et al., 2024; Sun et al., 2017). For instance, Ramezanzadeh et al. (2020) demonstrated that zinc anodes provide stable and predictable potential under controlled conditions; however, their performance significantly decreases in highly turbulent seawater, raising concerns about their long-term reliability in real marine operations. Similarly, Yadav and Kumar (2021) highlighted aluminum's superior current efficiency and lightweight properties, yet their study largely excluded the environmental sustainability issues associated with aluminum alloying elements, creating uncertainty about its broader application in maritime contexts. While both studies confirm the effectiveness of sacrificial anodes, they fail to integrate operational variability, sustainability considerations, and cost-effectiveness into a comprehensive framework.

This article aims to review the electrochemical performance and protection effectiveness of different sacrificial anode metals in marine applications, comparing their advantages, disadvantages, and optimal usage conditions. The contribution of this study lies in offering both theoretical insights by bridging fragmented research findings and practical implications for developing more effective, durable, and environmentally responsible cathodic protection strategies in the maritime industry.

RESEARCH METHOD

This study adopted a literature review approach by analyzing 45 scientific references from peer-reviewed journals, industry standards, and technical books published between 2000 and 2025. Keywords used in the search included sacrificial anode, cathodic protection, zinc anode, aluminum anode, magnesium anode, and marine corrosion. Data were classified based on anode material, electrochemical potential, corrosion rate, service life, and cost considerations. A comparative analysis was conducted to evaluate each anode's effectiveness under various seawater resistivity levels.

RESULTS AND DISCUSSION

Sacrificial Anode Working Principle

Sacrificial anodes work on the principle of electrode potential difference. The anode material has a more negative potential compared to the protected steel structure, making it preferentially oxidize. The general oxidation reaction is:

M→Mn++ne−M \rightarrow M^{n+} + ne^-M→Mn++ne−

The released electrons flow to the protected steel, preventing its oxidation.

Types of Sacrificial Anode Metals

Table 1. Anode Metals

Metal	Potential vs Ag/AgCl (V)	Density (g/cm^3)	Efficiency (%)	Service Life (years)	Main Characteristics
Zinc (Zn)	-1.05	7.13	90–95	2–5	Stable in seawater, widely used
Aluminum (Al)	-1.10	2.70	90–95	3–8	Lightweight, high efficiency
Magnesium (Mg)	-1.55	1.74	50–60	1–3	Highest potential, rapid consumption in seawater

Mechanism of Sacrificial Anode Cathodic Protection

As described previously, the principle of sacrificial anode cathodic protection (SACP) is to make the protected structure act entirely as a cathode. The sacrificial metal, having a more negative potential, corrodes preferentially, providing protective current to the steel surface. The magnitude of this current depends on:

1. Driving Voltage – the potential difference between the anode and the steel hull;
2. Seawater Resistivity – which influences current distribution;
3. Anode Geometry – larger exposed surface area delivers more current;
4. Flow Conditions – increased water flow enhances ion transport, which can increase anode consumption rates.

For example, magnesium anodes with an open-circuit potential (OCP) of around –1.55 V (Ag/AgCl) generate significantly higher current density compared to zinc (–1.05 V), but this comes with faster depletion of the anode mass.

Material-Specific Performance in Quantitative Terms

Zinc (Zn)

Zinc is the most widely used sacrificial anode material in the maritime industry due to its stability in seawater. With a current capacity of around 780 Ah/kg, zinc provides adequate protection for ship steel structures over a certain period. The average consumption rate is about 11.2 kg per year for a medium-sized bulk carrier hull, making it relatively economical for medium-term applications.

The main advantage of zinc is its predictable consumption pattern and very low risk of passivation. This makes zinc the standard choice for ships operating in waters with high to medium salinity, as its performance remains consistent under varying conditions. Additionally, zinc is widely available on the market, making it a more accessible solution for shipowners.

However, zinc’s drawback lies in its relatively high density, which increases the overall anode weight on larger ships. Although the added weight is not extreme, it still contributes to the vessel’s total mass and can slightly increase fuel consumption. Therefore, zinc is more suitable for conventional cargo ships or vessels where weight efficiency is not the main priority.

Aluminum (Al)

Aluminum offers far greater efficiency compared to zinc, with a current capacity of about 2,000 Ah/kg, nearly three times higher than zinc. This high current capacity means that aluminum anodes have a lower consumption rate, around 4.5 kg per year for similar hull protection, making them more cost-effective over the long term.

The key advantage of aluminum is its lightweight property, which reduces the vessel's overall weight and contributes to lower fuel consumption. This characteristic makes aluminum an excellent choice for high-speed vessels, passenger ships, or naval ships where weight efficiency directly impacts operational performance. Moreover, its high electrical efficiency further enhances cost savings through reduced maintenance needs.

Nevertheless, aluminum has some limitations, such as its tendency to passivate in seawater if not alloyed with elements like zinc or indium. It is also sensitive to galvanic coupling when used alongside corrosion-resistant materials such as stainless steel, which may reduce its effectiveness. Therefore, proper selection and system design are crucial when deploying aluminum anodes on ships.

Magnesium (Mg)

Magnesium has a current capacity of around 1,200 Ah/kg with a very high protective potential (approximately –1.55 V vs Ag/AgCl), making it highly effective in low-conductivity environments such as freshwater or brackish water. In these conditions, magnesium delivers strong protective currents, ensuring that the steel structure remains fully safeguarded against corrosion. For this reason, magnesium is commonly applied in tugboats or smaller vessels operating in rivers and brackish ports.

However, magnesium's consumption rate is much higher than that of zinc or aluminum, reaching around 15–20 kg per year in seawater. This rapid depletion makes it less economical for vessels operating in open oceans. The frequent need for replacement increases maintenance costs over the vessel's operational lifetime.

Another challenge with magnesium is the risk of overprotection when used in high-salinity seawater. Its high driving voltage can cause coating blistering and hydrogen evolution at the cathodic surface, which not only reduces protection effectiveness but may also damage the ship's hull coating. Therefore, magnesium is recommended primarily for freshwater or brackish environments rather than open-ocean applications.

Environmental Factors Influencing Performance

Water Salinity

Water salinity is one of the most influential environmental factors in determining sacrificial anode performance. In high-salinity seawater, conductivity is high, which reduces the resistance between the anode and cathode. This condition allows zinc and aluminum anodes to work efficiently because their driving potentials are sufficient to provide continuous protection without being wasted. Magnesium, however, often becomes less efficient in these conditions, as its high potential can cause unnecessary overprotection, leading to rapid depletion.

In brackish water, where conductivity is lower, magnesium's higher driving potential becomes an advantage. The strong current density produced ensures that the steel structure receives sufficient protection even in environments with reduced ion transport. This makes magnesium particularly valuable for vessels frequently operating in estuaries, rivers, and coastal areas where salinity fluctuates.

In freshwater environments, both zinc and aluminum are prone to passivation, which significantly reduces their effectiveness. Under these conditions, magnesium becomes the most effective choice, as its high potential prevents passivation and provides reliable cathodic protection. Therefore, the selection of sacrificial anode material should be tailored to the specific salinity profile of the operational environment (Anwar et al., 2021; Delwiche & Lydon, 2018; L, 2021; Melchers & Jeffrey, 2014; Rahman, 2019).

Water Temperature

Temperature has a direct effect on the rate of electrochemical reactions, influencing the speed at which sacrificial anodes are consumed. In warmer tropical waters, higher temperatures accelerate ion mobility and reaction rates, leading to increased anode consumption. For example, aluminum anodes deployed in tropical seas may consume 10–15% faster compared to those used in temperate waters, requiring more frequent monitoring and replacement.

In contrast, cold-water environments typically slow down electrochemical reactions. As a result, sacrificial anodes in such regions tend to last longer, extending service life and reducing maintenance costs. This makes colder regions more favorable for long-term anode performance, although protection levels must still be carefully monitored to prevent underprotection.

The temperature factor therefore plays a crucial role in predicting the longevity and efficiency of anode systems. Ship operators must consider seasonal and geographic temperature variations when designing cathodic protection systems, ensuring that anodes provide consistent protection across different climates.

Flow Rate and Turbulence

Flow rate and turbulence around a ship's hull strongly affect corrosion risk and the performance of sacrificial anodes. In areas of high flow, such as near propellers, rudders, and bilge keels, corrosion risk is significantly elevated due to constant water movement and oxygen replenishment. These zones typically require denser anode placement to ensure full protection coverage.

Turbulence also influences electrochemical reactions by increasing oxygen supply at the cathodic surface. This elevated oxygen level raises current demand from sacrificial anodes, thereby accelerating their consumption. Consequently, ships operating in turbulent or fast-moving waters must anticipate higher maintenance needs and more frequent replacement intervals.

Strategic placement of anodes in high-flow regions is essential to maintaining uniform protection. Computational modeling of current distribution can help determine optimal anode locations and densities, ensuring that vulnerable areas receive adequate defense against accelerated corrosion caused by turbulence.

Biofouling

Biofouling, or the accumulation of marine organisms such as algae, barnacles, and mussels on the hull, can alter corrosion dynamics significantly. These organisms create microenvironments that trap oxygen and moisture, forming localized corrosion cells that disrupt the protective current distribution from sacrificial anodes. As a result, some areas of the hull may remain underprotected despite overall system functionality.

The presence of biofouling increases current demand, as the anodes must compensate for additional localized corrosion risks. In severe cases, biofouling can shield certain hull areas, making it difficult for protective currents to reach those surfaces effectively. This situation can accelerate hull deterioration and increase maintenance needs.

To address these challenges, regular hull cleaning and the use of antifouling coatings are essential complements to cathodic protection systems. By minimizing biofouling, ship operators can ensure that sacrificial anodes distribute their protective current more evenly, extending system effectiveness and maintaining structural integrity.

Consumption Patterns and Maintenance Planning

Practical implementation of SACP requires predicting consumption to schedule anode replacement during dry-docking.

1) Zinc: Generally replaced every 2–3 years in ocean-going vessels.
2) Aluminum: Can last 4–6 years with proper placement.
3) Magnesium: Often replaced annually in brackish/freshwater ships due to fast depletion.

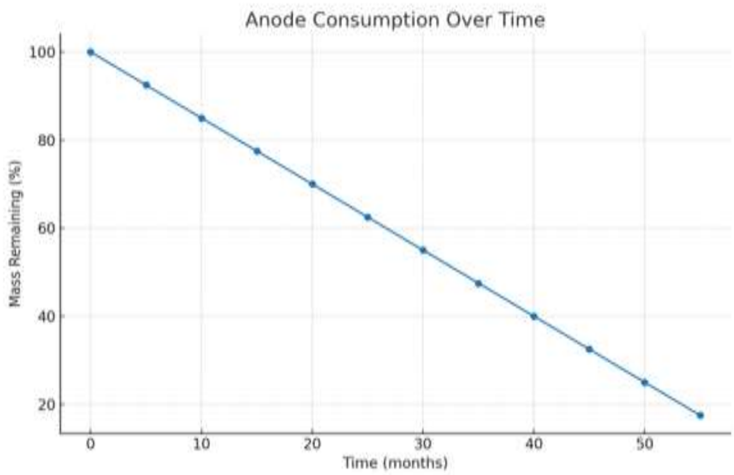

Figure 1. Patterns and Maintenance Plannin

Comparative Case Analysis

Table 2. Comparative Analysis

Vessel Type	Operating Water	Chosen Anode	Protection Potential (V, Ag/AgCl)	Replacement Interval	Remarks
Oil Tanker (VLCC)	Tropical Seawater	Aluminum	–1.05 to –1.10	5 years	Chosen for weight savings and long life
Tugboat	Brackish	Magnesium	–1.45 to –1.50	1.5 years	Needed high driving voltage for effective protection
Bulk Carrier	North Atlantic	Zinc	–1.03 to –1.06	3 years	Stable performance in cold water
Fast Ferry	Mediterranean	Aluminum	–1.05 to –1.09	4 years	Reduced fuel consumption due to lighter anodes

From these examples, aluminum offers the best life-cycle economy in most seawater environments when weight is a consideration, while zinc remains a reliable option for standard ocean-going vessels without strict weight limitations. Magnesium is a niche solution.

Future Material Innovations

Future material innovations in sacrificial anode technology are currently focused on developing hybrid anodes that combine sacrificial and impressed current systems to achieve optimized performance, creating environmentally friendly alloys such as indium-free aluminum to reduce heavy metal leaching and meet stricter environmental standards, and advancing smart anodes equipped with sensors that can monitor their own consumption and transmit data wirelessly to enable predictive maintenance, thereby improving efficiency, sustainability, and reliability of cathodic protection systems in real-world marine applications (Jawad et al., 2020; Kirchgeorg et al., 2020; Knudsen et al., 2024; H. Li et al., 2025).

CONCLUSION

This literature review concludes that no single sacrificial anode material is universally optimal for all ship types and environments; instead, material selection must be tailored to operational profiles, environmental conditions, and maintenance schedules. Zinc remains the industry standard for seawater applications due to its predictable performance and affordability, aluminum provides superior weight efficiency and service life suitable for high-speed or naval vessels, while magnesium delivers the highest driving voltage for low-conductivity environments but is less economical in open oceans due to rapid consumption. The findings emphasize the importance of conducting resistivity surveys, employing mixed-material systems for multi-environment vessels, and utilizing computational modeling to ensure uniform current distribution. From an industrial perspective, optimized sacrificial anode cathodic protection (SACP) systems reduce dry-docking frequency, cut maintenance costs, and enhance fuel efficiency, leading to significant lifetime savings. Future research should focus on developing recyclable, non-toxic anode alloys, integrating SACP with real-time monitoring for predictive maintenance, and exploring hybrid systems that combine the strengths of SACP and ICCP. Overall, sacrificial anodes remain central to marine corrosion protection, and ongoing advancements in materials science and monitoring technologies will further enhance their effectiveness, sustainability, and contribution to safer, more economical shipping operations.

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