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Review

An Research Overview of Corrosion and Protection Technologies for Offshore Platforms

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Abstract: As a critical component of infrastructure that facilitates the development of marine resources, energy production, and scientific research, offshore platforms are frequently subjected to various hazards, including structural corrosion and connection failures, which arise from the challenging conditions of marine environments. In extreme cases, these issues can lead to significant production accidents and financial losses. This article begins by outlining the background of corrosion affecting offshore platforms. It subsequently discusses the different types of corrosion and their underlying causes in detail, concluding that these platforms primarily encounter several forms of corrosion, including electrochemical corrosion, microbial corrosion, and stress corrosion, with electrochemical corrosion being the most prevalent. From a phenomenological standpoint, corrosion can be categorized into localized corrosion and uniform corrosion. The article further elaborates on various anti-corrosion technologies, encompassing the selection of corrosion-resistant materials, electrochemical protection methods, and coating protection strategies. The principal conclusions drawn indicate that stainless steel, titanium alloys, and specialized corrosion-resistant alloys are commonly employed in offshore platforms. Additionally, the efficacy of the sacrificial anode method is significantly influenced by temperature. The external current method proves advantageous for the anti-corrosion of large structures, while organic coatings, such as epoxy coatings, and inorganic coatings, including zinc-rich

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coatings, are also discussed. This article offers a systematic and comprehensive perspective, serving as a technical reference for anti-corrosion research related to offshore platforms.

Keywords: Offshore platforms; types of corrosion; anti-corrosion technologies; anti-corrosion materials; cathodic protection; coating protection

1. Background of Corrosion Protection for Offshore Platforms

The Offshore platforms, including drilling platforms, wind power generation platforms, wind power installation platforms, and oil and gas production platforms, are essential infrastructures that support marine resource development, energy production, and scientific research. The corrosion issues faced by these platforms not only impact their functionality and safety but can also lead to pollution and damage to the marine ecosystem. If the corrosive problems in the ocean are not effectively addressed, they will further exacerbate the deterioration of offshore platforms. Increasing levels of corrosive substances, such as chloride ions, dissolved oxygen, and sulfides, will intensify the corrosion of these structures. Therefore, the development and implementation of effective anticorrosion technologies for offshore platforms are crucial for ensuring the safety and longevity of marine engineering structures[1].

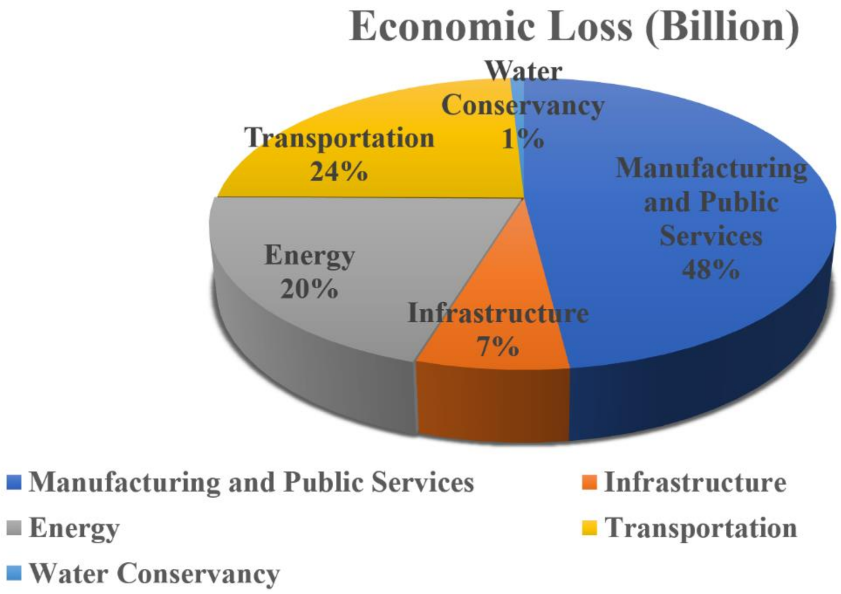

Figure.1. Economic losses due to corrosion problems[2]

With the rapid development of the marine economy, the Chinese government has prioritized the protection and sustainable development of marine resources, viewing the advancement of the marine corrosion protection industry as a key strategic necessity. The evolution of corrosion protection technology for offshore platforms fosters the application of new materials and advanced coating techniques, continually driving scientific and technological innovation. Economically, corrosion protection for offshore platforms is crucial for ensuring operational safety and reliability, as well as extending the service life of marine engineering and ships. According to global corrosion research, the economic loss caused by corrosion worldwide averages approximately 3.4% of the global gross national product (GNP). In China, corrosion-related losses are estimated to be around 5% of the gross domestic product (GDP)[3], which is significantly higher than in other countries. Of particular concern is that corrosion losses in the marine environment account for about one-third of total corrosion losses[4], underscoring the urgency and importance of addressing corrosion issues on marine platforms. Technological innovation is a key factor in advancing progress in this field, while the support of national policies and strategic planning serves as a crucial driving force to accelerate the research and application of new technologies.

With the increasingly fierce competition in the development and utilization of global marine resources, China's advancements in technology and improvements in service levels in this sector are crucial for engaging in international competition and expanding overseas markets. Continued policy support and strategic planning at the national level will further promote the development of marine corrosion protection technology, thereby safeguarding national interests and fostering sustainable development.

2. Research on Corrosion of Offshore Platform

Understanding the mechanisms and characteristics of various types of corrosion is essential for developing effective protection strategies, such as coatings, cathodic protection, and material selection. Classifying corrosion types allows for a more accurate assessment of the corrosion risk associated with offshore platforms, enabling targeted protection in specific subregions while avoiding over-protection and unnecessary costs. In conclusion, a comprehensive understanding of corrosion classification forms the foundation of corrosion management for offshore platforms and is crucial for ensuring the safe, reliable, and economical operation of these structures. By gaining deeper insights into corrosion types, more effective protective measures can be implemented to extend the service life of offshore platforms and enhance overall operational efficiency.

Figure.2. Significant metal losses caused by corrosion on offshore platforms[5].

2.1 Causes of Corrosion and Its Classification

The causes of corrosion encompass a wide range of types, including electrochemically induced corrosion, galvanic coupling corrosion, corrosion due to uneven oxygen concentration, and stress corrosion[6]. Electrochemical corrosion is the most prevalent form and involves an electrochemical reaction between the metal and an electrolyte (e.g., seawater), which generates a current loop that accelerates the corrosion process. Microbiological corrosion is initiated by marine microorganisms that produce acids, bases, and oxidants, while physical wear and tear also contribute to the acceleration of corrosion. Stress corrosion cracking results from the combined effects of stress and a corrosive environment, commonly occurring in high-stress areas. Galvanic corrosion occurs when different metals come into contact, with one metal acting as an anode and accelerating corrosion, while the other metal is protected as a cathode. Chemical corrosion arises from corrosive chemicals that react with the metal surface, forming oxides, sulfides, or salt products, which ultimately lead to corrosion.

Corrosion phenomena on offshore platforms can be classified into two types: uniform corrosion and localized corrosion[7]. Uniform corrosion refers to the degradation that occurs across most areas of the metal surface, characterized by a relatively slow corrosion rate. However, it can have widespread effects and poses a significant threat to structural integrity. In contrast, localized corrosion affects only a small area, such as welded joints or areas with coating damage. This type of corrosion can lead to rapid deterioration due to variations in oxygen or ion concentrations, often initiated by unaddressed coating damage. Homogeneous corrosion is a prevalent form of corrosion characterized by a relatively slow rate, typically resulting in a uniform loss of material from the metal's surface. This process leads to consistent rusting or etching and often occurs on steel structures exposed to marine atmospheric and seawater total immersion zones. Homogeneous corrosion tests carried out by SOARES et al. have shown that the corrosion process of steel tubes can be divided into multiple stages. Additionally, the variation in corrosion rate over time is commonly described using non-linear models[8]. Based on the nonlinear corrosion model developed by Guedes Soares and Garbatov, Cui Jinju et al. utilized a combination of Log-normal distribution, Monte Carlo simulation, and Gaussian Process to simulate the progression of uniform corrosion, which provides important theoretical support for the prediction of the durability of ship structures under long term severe sea conditions. It provides important theoretical support for predicting the durability of ship structures under prolonged exposure to severe sea conditions[9]. Localized corrosion is the phenomenon in which corrosion occurs in a specific area on a metal surface. Unlike uniform corrosion, which affects the entire surface evenly, localized corrosion is confined to a small region, often resulting in a higher corrosion rate. Common types of localized corrosion include pitting corrosion, crevice corrosion, and fatigue corrosion. In the pile leg structures of offshore platforms, localized corrosion can arise from factors such as scouring by water currents, the attachment of marine organisms, and the concentration of salts and other corrosive substances in seawater. Notably, the bottom part of the pile leg that is in contact with seawater is particularly susceptible to localized corrosion due to the combined effects of seawater corrosion and fouling by seabirds[10]. Rius Planas et al. investigated the effects of pitting-induced isolated pits and long pits (grooves along the weld) on fatigue life. They found that the reduction in cross-section, partly attributed to the fatigue notch factor of the corroded pits, has significant implications for enhancing the safe life of offshore platforms[11].

Table 1. Mechanisms and descriptions of several types of corrosion [12]-[15]

Corrosion Type	Mechanism	Description
Electrochemical corrosion	Metals Experience Electron Loss During Current Cycling	Metals exhibit reactivity when in contact with electrolytes, including seawater.
Microbial Corrosion	The Action of Microorganisms Results in the Production of Acids and Bases.	Marine microorganisms are capable of synthesizing acids, bases, oxidizers, and a variety of other compounds that function as initiators.
Stress Corrosion Cracking	The interplay between stress and a corrosive environment.	Commonly observed in areas characterized by high levels of stress.
Galvanic Corrosion	The contact between different metals can generate a galvanic battery effect.	One metal facilitates the process of corrosion, while the other metal is safeguarded against it.
Chemical Corrosion	The reaction of a chemical with a metal result in the formation of an oxide, among other products.	The formation of oxides, sulfides, or salts.

2.2 Corrosion environment zoning of offshore platforms

Based on the variations in the marine environment, the corrosion areas can be categorized into the atmospheric zone, splash zone, tidal zone, full immersion zone, and seabed mud zone. Each of these marine corrosion zones is associated with a distinct corrosion rate.

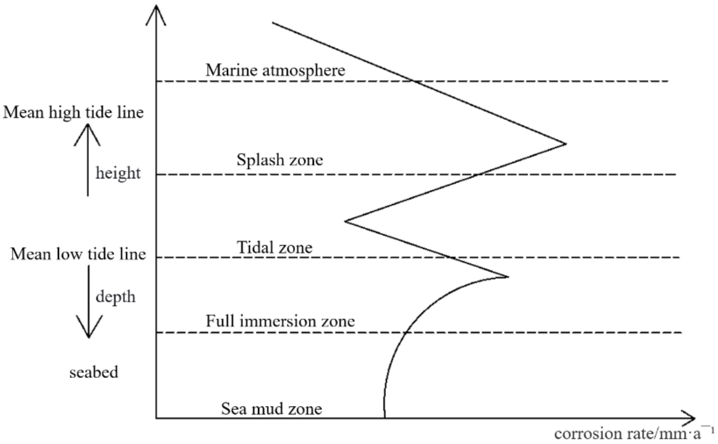

Figure.3. Corrosion partitioning and corrosion rate relationship in a marine environment[16]

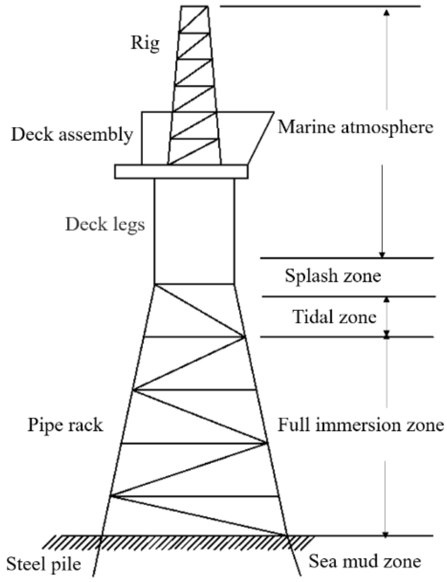

Figure.4. Platform main structure and its corrosion partitioning[17]

2.2.1 Atmospheric zone

The atmospheric zone refers to the region above the sea surface splash zone and the coastal atmospheric zone, where corrosion primarily occurs due to oxidation processes. These processes are triggered by the interaction of water vapor and oxygen in the air. In environments characterized by high humidity and elevated temperatures, the formation of electrolyte solutions on metal surfaces accelerates, promoting corrosion reactions. Components of the platform located above the splash zone—such as the group block, deck structure, upper parts of the conduit rack, and living area module—are subjected to prolonged exposure to harsh conditions, including salt spray and sunlight, which significantly increases the corrosion rate. Furthermore, the presence of sulfur dioxide (SO2) in the marine atmosphere can further accelerate this rate of corrosion. Consequently, it is often necessary to apply rust-resistant paints, coatings, or other surface treatment techniques to protect against corrosive agents in the air.

2.2.2 Splash zone

The term refers to the region situated above the mean high tide line and below the designated low tide line, typically located in proximity to the tide line. This area is characterized by corrosion primarily resulting from the direct interaction between seawater and air, compounded by the significant impact effects of seawater. It encompasses regions that intermittently experience contact with both air and water due to the influence of waves and tides, such as the areas adjacent to the waterline of ship hulls and offshore platforms. To enhance the longevity of critical structures, such as pile legs, within the marine environment and to mitigate production costs, it is essential to address the corrosion of metallic materials located within the wave splash zone[18]. In addition to employing high-performance anti-corrosion coatings, the implementation of electrochemical protection methods, such as cathodic protection, may also be necessary.

2.2.3 Tidal zone

The tidal zone is the area between the mean high tide level and the mean low tide level, influenced by tidal actions. In this zone, the metal surface is periodically in contact with seawater, which provides a sufficient supply of oxygen[19]. The corrosion environment is complex; the oxygen concentration on the steel surface above the water is significantly higher than that below the water surface. This difference in oxygen concentration leads to differential corrosion, resulting in a higher corrosion rate. Additionally, this phenomenon affects the durability of concrete structures. To mitigate tidal corrosion, special coatings that are resistant to such conditions should be applied in the tidal zone, potentially in combination with protective techniques like sacrificial anodes.

2.2.4 Total immersion zone

The total immersion zone refers to areas that are completely submerged underwater, such as the submerged sections of ships, underwater pipelines, and the underwater structures of offshore platforms. In this zone, electrochemical corrosion is predominant. Under the influence of dissolved oxygen, the anode experiences corrosion due to its high potential state, while a portion of the cathode area is protected because it exists in a low potential state[20]. Additionally, biochemical corrosion can occur due to underwater microorganisms, sulfides, and other factors. In the total immersion zone, anti-corrosion coatings combined with cathodic protection are typically employed. These coatings must possess excellent water resistance and anti-microbial properties to effectively mitigate erosion.

2.2.5 Submarine mud zone

The submarine mud zone primarily consists of submarine sediments and is typically associated with submarine pipelines, cables, and infrastructure. This area is characterized by high salt content and low resistivity. Steel buried in the sea mud experiences lower corrosion rates due to low oxygen content and low dissolved oxygen concentration compared to fully immersed areas. However, if corrosive microorganisms are present, their metabolic activity can accelerate the corrosion of the metal. To mitigate this risk, it is common to employ coatings and cathodic protection, in addition to using corrosion-resistant insulation and wrapping materials, to prevent corrosive substances in the sea mud from contacting the surface of the structure[21].

3 Research on Corrosion Prevention Technology

To address the issue of corrosion on offshore platforms in harsh marine environments, experts and scholars have implemented a variety of strategies to prevent and control this deterioration. Common and effective methods for preventing corrosion of metal materials include material selection, electrochemical protection, coating protection, and the use of corrosion inhibitors, among other techniques[22].Among these, the selection of materials and corrosion protection strategies for offshore platforms is essential to ensuring their long-term stability and safety. In material selection, factors such as corrosion resistance, mechanical strength, and cost-effectiveness must be considered. The electrochemical protection method prevents metal corrosion through sacrificial anodes or applied current, while the coating protection method employs organic or inorganic coatings to physically isolate the metal from the corrosive environment. The rational selection of these methods and their comprehensive application are crucial for safeguarding the structural integrity of offshore platforms in harsh marine environments.

3.1 Research on Material Selection for Offshore Platforms Considering Multiple Factors

In the discipline of ocean engineering, the selection of essential structural components for offshore platforms constitutes a critical task that significantly influences the structural integrity, operational expenses, and environmental sustainability of the platform. As technological advancements continue and the demand for environmental conservation escalates, this selection process has become increasingly intricate and demanding. Consequently, it is imperative to undertake a comprehensive evaluation of various factors when choosing materials, including performance metrics, cost-effectiveness, environmental implications, construction technology prerequisites, and long-term maintenance considerations.

In the field of ocean engineering, the selection of materials must take into account their corrosion resistance, mechanical strength, and cost-effectiveness. For instance, steel skeleton plastic composite pipes, which integrate the corrosion resistance of metal pipelines with the high strength characteristics of metal steel wires, effectively address the challenges of pressure resistance and corrosion that are inherent in both metal and pure plastic pipelines. These composite pipes are extensively utilized in water injection systems for offshore platforms, as well as in offshore oil drilling and extraction equipment[23]. Research conducted by Tverberg indicates that the sensitivity of stress corrosion cracking is influenced by the nickel content in stainless steel, with variations observed as nickel content increases[24]. Consequently, stainless steel grades such as 304/304L and 316/316L exhibit a greater susceptibility to stress corrosion cracking due to their elevated nickel proportions. In contrast, the sensitivity to stress corrosion cracking in 2205 duplex stainless steel is significantly lower than that of 304 and 316 stainless steels. This finding suggests that in marine environments, particularly under conditions of high temperature, high humidity, and salt spray, 2205 duplex stainless steel demonstrates superior resistance to stress corrosion cracking[25]. Furthermore, Chen Jingqi et al. developed copper/carbon steel composite thin strips through a cold rolling process, optimizing their properties by controlling the thickness and microstructure of the material. This approach enhanced the interfacial bonding strength and eliminated residual stress, thereby providing a scientific basis and technical support for the anti-corrosion efforts of offshore platforms, ultimately improving their safety and economic viability[26]. Currently, the decks of the US Navy's aircraft carriers utilize HSLA115 steel, which possesses a maximum yield strength of 785 MPa, making it suitable for the manufacturing of large-scale marine equipment[27]. Additionally, low-carbon steel containing copper, specifically 0Cu2Cr (which includes 2.5% Cu), has demonstrated promising application prospects in marine environments due to its excellent corrosion resistance and antifouling properties[28].

Environmental impact is a critical factor to consider when selecting materials. For instance, in deep-sea environments, titanium alloys are susceptible to stress corrosion cracking due to elevated chloride concentrations and low oxygen levels. Consequently, the surface condition and microstructure of these alloys significantly influence the likelihood and rate of stress corrosion[29]. Additionally, microbial corrosion is another form of corrosion that is heavily influenced by environmental conditions. AlAbbas et al. investigated the impact of sulfate-reducing bacterial biofilms on the corrosion behavior of low-alloy high-strength steel (API-5L X80). Through a series of experiments and analytical techniques, they examined the corrosion behavior of sulfate-reducing bacteria (SRB) on this high-strength carbon steel within oil and gas transportation systems, highlighting the propensity of bacteria to colonize welding areas, particularly heat-affected zones[30]. Liu et al. demonstrated through Environmental Scanning Electron Microscopy (ESEM), Energy Dispersive Spectroscopy (EDS), and X-ray Photoelectron Spectroscopy (XPS) that 2205 duplex stainless steel is predominantly affected by microbiologically induced corrosion (MIC) in marine environments. They proposed a hypothesis regarding the symbiotic proliferation of SRB and sulfate-oxidizing bacteria (SOB) to account for the observed high corrosion rates[31].

In the context of long-term maintenance, the preparation processes for copper/steel composite materials—including the explosive composite method, rolling composite method, and diffusion composite method—demonstrate the capability to achieve effective metallurgical bonding and high interface strength, thereby contributing to a reduction in long-term maintenance costs. The South China Sea region, characterized by elevated humidity and temperature, experiences rapid corrosion rates, rendering traditional steel inadequate for meeting performance demands. Consequently, the selection of materials such as stainless steel, titanium alloys, or specially treated corrosion-resistant alloys becomes imperative. The primary corrosion-resistant elements, including nickel (Ni) and chromium (Cr), are typically incorporated either individually or in conjunction with trace elements such as tin (Sn), antimony (Sb), and copper (Cu), which enhance corrosion resistance and alleviate the long-term maintenance burden[32]. Tian Yuwan et al. employed micro-solution electrochemical testing technology to investigate the corrosion electrochemical mechanisms of chromium-containing low-alloy high-strength corrosion-resistant steel bars within micro-porous environments. Their analysis revealed a correlation between these mechanisms and the natural corrosion outcomes observed in reinforced concrete. They concluded that an increase in pore volume correlates with an accelerated rate of local corrosion in the steel bars, with the local corrosion rate being directly proportional to the logarithm of the pore liquid volume [36].

3.2 Electrochemical protection method

There are two primary types of electrochemical protection methods: sacrificial anode protection and applied current cathodic protection.

3.2.1 Sacrificial anode method

Sacrificial anodes protect the host metal by placing metals with different electrochemical potentials in contact with one another to form a microcell. In the electrochemical protection mechanism, the metal with the lower potential serves as the anode, which accelerates its own corrosion rate and thereby protects the host metal. Conversely, the metal with the higher potential functions as the cathode, which slows down the corrosion process. This method is suitable for small projects and is relatively easy to install and maintain; however, it has limited effectiveness in high-resistance environments. Sacrificial anodes, composed of highly reactive metals such as magnesium, zinc, or aluminum, are installed on seawater-exposed components of the platform, including conduit racks and risers, to protect them from corrosion. However, the effectiveness of the sacrificial anode method diminishes in high-resistance soils or media, which limits its applicability. Additionally, replacing spent anodes can be challenging or costly, making it potentially uneconomical for structures with high current demands. Long Ping et al. tested and analyzed the electrochemical performance of Al-Zn-In-Sn sacrificial anodes in various environments and concluded that this method provides superior corrosion protection in low-temperature, inter-immersion conditions, but accelerates corrosion at elevated temperatures[37].Zhang and his team conducted a series of experiments to thoroughly investigate the root cause of the failure of the anticorrosion coating and cathodic protection system in the seawater ballast system of the FPSO (Floating Production Storage and Offloading Unit) within the offshore petroleum engineering environment, where temperatures exceed 50°C. They concluded that employing aluminum alloy sacrificial anodes in high-temperature or alternating dry and wet environments significantly enhances temperature resistance, extends service life, and improves protective efficacy[38]. Robinson H. A. et al. designed a system to achieve efficient protection of metallic structures by utilizing two magnesium sacrificial anodes with varying output rates[39]. Kunio Watanabe et al. developed a range of alloy formulations for sacrificial anodes that provide effective corrosion protection in reinforced concrete structures[40].

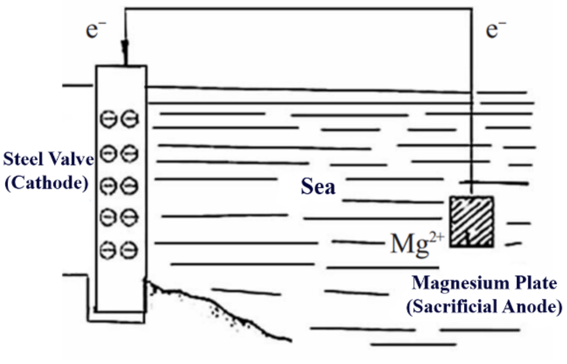

Figure.5. Schematic map of cathodic protection method with magnesium sacrificial anode[41]

3.2.2 External current cathodic protection method

Applied current cathodic protection is a technique used to safeguard metal structures by utilizing a direct current power supply. By connecting an external direct current(DC) power source to an auxiliary anode, the metal structure being protected acts as a cathode, facilitating a protective electrochemical reaction on its surface. This process leverages the flow of electric current to slow down or halt metal corrosion. This method offers a significant advantage in terms of efficiency, as it can deliver a current strong enough to protect large or complex structural components. However, it is more expensive to install and maintain compared to the sacrificial anode method, and the complexity of system design and installation requires specialized personnel for operation. To ensure the effectiveness of the applied current protection method and minimize its drawbacks, it is essential to conduct a comprehensive preliminary study. This study should focus on understanding the various factors influencing corrosion, such as soil resistivity, piping materials, and the surrounding environment. Such an analysis provides a foundation for the arrangement of auxiliary anodes, the placement of reference electrodes, and the selection of rectifiers and transformers. Feng Jiaquan and other researchers utilized numerical simulation technology through computer software to develop a model for applied current cathodic protection for the main hull structure of the target Floating Production Storage and Offloading (FPSO) unit. This model enabled a detailed analysis of how the layout, quantity, and current output of auxiliary anodes in the applied current cathodic protection system impact the protective effectiveness for the target FPSO[42]. Additionally, Wendy Yang and colleagues constructed an experimental ship corrosion prevention system that harnesses wave energy and the Seebeck effect, effectively mitigating electrochemical corrosion and inhibiting microbial corrosion to some extent[43]. By comparing various repair strategies, Chen Baiyun demonstrated that the applied current cathodic protection method can effectively restore damaged concrete structures[44]. Li Zengguo conducted experiments on the electrochemical processes involved in steel corrosion in seawater. He analyzed the fundamental working principles of the applied current cathodic protection method and discussed the role of the constant potential meter, the arrangement and protection of the auxiliary anode, and experimentally verified the functions and effects of the components of the cathodic protection system[45]. Zheng Yufeng proposed an underwater rapid repair technology utilizing the applied current method. He designed a comprehensive underwater rapid repair device that combines technical practicality with effectiveness. This device successfully addresses the local cathodic protection of offshore structures, enabling efficient repairs to marine structures. Its stability and effectiveness were validated through real-sea experiments[46]. The cathodic protection device developed by Yue Qiang et al. effectively provides cathodic protection for marine structures by selecting auxiliary anode materials and control methods that are suitable for seawater environments. This approach significantly slows or prevents corrosion, ensuring the safety of the structures and prolonging their service life[47]. Using sacrificial anode design calculations, E.S. Ameh et al. concluded that 3,620 magnesium alloy anodes would need to be connected to ensure a 40-year design life for an offshore X42 steel pipeline. This comparison highlights the benefits of applied current systems in delivering long-term, continuous protection, particularly for large-scale and long-lasting pipeline projects[48]. For cathodic protection of offshore platforms, both the sacrificial anode protection method and the impressed current protection method can be employed. In contemporary engineering practice, these two methods are often used in conjunction to maximize the efficiency of cathodic protection for offshore platforms by leveraging the advantages of each approach. Dalian Comal Marine Science and Technology Co., Ltd. has successfully developed an integrated device for tensioned impressed current cathodic protection and monitoring for offshore in-service platforms. This device effectively prevents both over-protection and under-protection of conduit racks, ensuring comprehensive protection of the platform throughout its entire life cycle. The tensioned impressed current cathodic protection system offers benefits such as low cost and minimal installation workload. Additionally, the system incorporates cathodic protection monitoring for newly constructed conduit racks, allowing for simultaneous use. For newly built conduit racks, installation can be completed at the manufacturing site, further reducing both installation costs and associated risks[49]. In addition to these two common cathodic protection methods, various other techniques, such as intermittent cathodic protection, are also available[50]. The multilayer distributed marine corrosion and protection database developed by the 725 Research Institute of China Shipbuilding Industry serves as a valuable reference for engineers and technicians specializing in marine environment corrosion and protection[51]. Furthermore, the cathodic protection system for marine platforms, collaboratively developed by the Fujian Institute of Physical Structure of the Chinese Academy of Sciences and the South China Sea Institute of Oceanography, has been widely adopted and implemented in the deep-water areas southeast of the Pearl River Estuary and in the oil and gas fields of the Beibu Gulf[52].

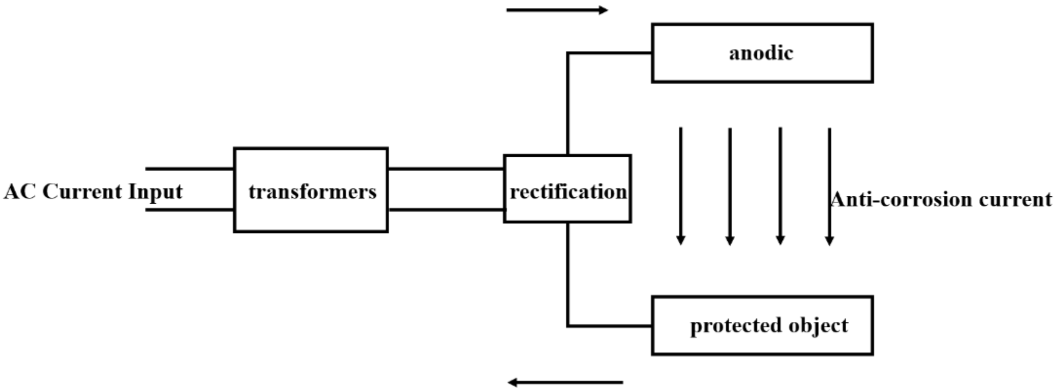

Figure.6. Schematic map of cathodic protection method with magnesium sacrificial anode[53]

3.3 Coating protection

Coating protection is currently categorized into two primary types: organic and inorganic coatings.

3.3.1 Organic coating

Organic coatings primarily consist of polymer resins, including epoxy resin, polyurethane, and acrylic, among others. The primary mechanism of action is physical isolation, which involves the barrier effect of the coating that prevents direct contact between corrosive substances and the metal surface. The coatings predominantly utilized in this context include polyurethane, polyethylene, epoxy, and phenolic coatings.Epoxies exhibit remarkable adhesion, dispersion, and mechanical properties, as well as superior resistance to corrosion and water. However, they demonstrate inadequate resistance to moisture, heat aging, and strong acids[54]. Among various epoxy formulations, thick-coated epoxy resins, zinc-rich primers, and polyurethane coating systems are noted for their exceptional resistance to weathering and chemical exposure[55]. Despite these advantages, epoxy resins face challenges, including limited weathering resistance and poor adhesion to non-polar plastics. During the 'Eleventh Five-Year Plan' period, the Institute of Oceanography of the Chinese Academy of Sciences (IOCAS) developed a proprietary anti-corrosion and repair technology for marine steel structures located in the wave splash zone. This technology, which can be applied in wet conditions, utilizes a novel anticorrosive method involving compound mineral resin cladding. This approach significantly enhances the anticorrosive performance and durability of the compound mineral resin cladding technology[56]. Meysam Toozandehjani et al. conducted a study examining the incorporation of aluminum-containing powders as reinforcing agents in epoxy resin coatings to improve the corrosion protection of carbon steel substrates. The impact of these additives on the corrosion resistance of the coatings was evaluated using electrochemical impedance spectroscopy (EIS) and Tafel polarization tests[57]. Research conducted by the Natural Gas Research Institute, along with associated research and development centers and testing facilities of PetroChina's Southwest Oil and Gas Field Company, demonstrated through simulated immersion experiments under various operational conditions that corrosive factors present in sour gas field pipelines significantly diminish the efficacy of epoxy anticorrosion coatings. This finding indicates a pressing need for further optimization of anticorrosive strategies to enhance the corrosion resistance of pipelines[58]. Zhang Ruizhu et al. investigated the performance of epoxy glass scale as a heavy-duty anticorrosion coating at the School of Mechanical Engineering, North China University of Water Conservancy and Hydropower. Their findings revealed that the unique layered structure of this coating effectively mitigated the penetration of corrosive media[59]. Mohammad Asif Alam et al. optimized the formulation of coatings by varying the type and concentration of curing agents to enhance their protective capabilities in harsh marine environments. They employed advanced characterization techniques, such as Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), nanoindentation, and Electrochemical Impedance Spectroscopy (EIS), to evaluate and understand the performance and durability of the coatings[60]. Gaber, M. A. W. conducted comparative testing of liquid epoxy primers and fusion-bonded epoxy primers concerning the mechanical properties of three-layer polyethylene coatings. The findings indicated that fusion-bonded epoxy primers demonstrate superior adhesion and cathodic protection[61].

Polyurethane coatings represent a multi-component synthetic resin system primarily synthesized through the reaction of isocyanates and polyols. This material amalgamates the flexibility, rapid curing, and chemical and abrasion resistance characteristic of organic polymers with the hardness and aging resistance typical of inorganic substances. The operational mechanisms of polyurethane coatings encompass various functions, including serving as a physical barrier, facilitating chemical bonding, and forming protective films. These coatings find extensive applications across diverse sectors, including construction, automotive, and electrical and electronic industries. In China, the production capacity and output of polyurethane have exhibited consistent annual growth, surpassing 90,000 tonnes in 2023. This expanding market has prompted technological innovations, enhancements in product performance, and an increased focus on environmental protection and sustainable development. For instance, Qing Ning et al. successfully synthesized an organic cinnamon copolymerized modified polyurethane emulsion utilizing polyvinyl acetate polyol, organic cinnamon oligomers, polyisophoric acid, a chain extender, and a hydrophilic chain extender as primary raw materials[62]. Wang Jianchuan et al. developed a waterborne two-component polyurethane topcoat characterized by high hardness, excellent adhesion, and superior chemical and weathering resistance, making it suitable for demanding outdoor working conditions[63]. Feng Zhiqiang and colleagues successfully formulated a modified polyurethane grouting material tailored for underground applications in mining by enhancing traditional polyurethane grouting materials with silicates[64]. Zong Hongliang and his team synthesized polyether GJ-480 for water-soluble polyurethane grouting material by employing small molecule alcohols with varying functionalities as compound initiators, resulting in a product with high water absorption capacity and favorable physical properties, thereby fulfilling the requirements for leakage and seepage prevention across various projects[65]. M. Salzano de Luna has conducted a series of tests, including immersion tests, salt spray tests, kinetic potential polarization (commonly referred to as Tafel polarization), and electrochemical impedance spectroscopy (EIS) measurements. These methodologies were employed to qualitatively and quantitatively analyze polyurethane coatings and assess their corrosion stability[66].

Polyethylene-based coatings are widely utilized plastic coatings known for their excellent chemical stability, low-temperature wear resistance, electrical insulation, low water absorption, and mechanical strength, among other advantages. In China, the production capacity of polyethylene continues to expand, with production reaching 25.32 million tonnes in 2022, while demand amounted to 34.2739 million tonnes. Notably, China's imports of polyethylene have decreased, whereas exports are experiencing an upward trend. It is anticipated that China will sustain its growth capacity within the polyethylene industry and further advance the development of high-end products through enhanced technological innovation[67]. The research team from Hebei Zhongke Tongchuang Science and Technology Development Co., Ltd. in collaboration with Shenyang University of Architecture has developed a high-adhesion polyethylene powder coating by selecting optimal polyethylene raw materials and incorporating a tackifying resin[68]. Li Jingfu has formulated a coating with superior sealing properties utilizing highly chlorinated polyethylene resin, following extensive testing[69]. Xu Yao et al. demonstrated that the ratio of curing agent to epoxy resin significantly influences adhesion in steel structures, as evidenced by bond strength tests on concrete surfaces, which averaged approximately 3.09 MPa. The optimal ratio was determined to be 0.6, yielding a maximum adhesion of approximately 8.3 MPa[70]. Furthermore, Wang et al. found that the capacitive arc diameter of aluminum-ultra-high molecular weight polyethylene (UHMWPE) composite coatings exceeded that of pure aluminum coatings, as revealed by electrochemical impedance spectroscopy tests, indicating superior barrier properties of the composite coatings[71].

3.3.2 Inorganic coating

Inorganic coatings possess distinctive chemical and physical properties that render them particularly suitable for application in chemical facilities and structures situated in marine environments. They play a crucial role in the domain of corrosion protection. Typically, these coatings exhibit high resistance to acids, alkalis, and a diverse array of chemicals. Furthermore, they demonstrate excellent water resistance, effectively preventing the infiltration of water and water-soluble salts that could compromise steel integrity. Additionally, inorganic coatings are less vulnerable to atmospheric factors, including ultraviolet light, oxygen, and ozone. Consequently, elements such as nickel play a crucial role as one of the primary corrosion-resistant components in the environmental weathering steel utilized in the South China Sea. The corrosion process leads to the formation of a nanostructured NiFe2O4, which refines the organization of the rust layer. The nickel-containing rust layer exhibits cation selectivity, effectively isolating Cl- ions from the exterior of the rust layer, thereby preventing the occurrence of chemical corrosion. He Yueying et al. conducted a comprehensive study on the properties, applications, and preparation methods of copper-carbon steel composites at the Hebei Steel Coating and Anti-corrosion Technology Innovation Centre. These composites are extensively utilized due to their resistance to corrosion and oxidation, high strength, and superior electrical and thermal conductivity. The authors also investigated various preparation techniques, including electroplating, solid-solid composites, and solid-liquid composites. Furthermore, they identified the challenges and issues encountered by these methods in practical applications[72]. Furthermore, Liu Jintao et al. conducted an investigation into the interfacial characteristics of copper/carbon steel explosion-welded composite plates. Their findings indicated that copper and iron atoms exhibited mutual diffusion at the interface, and all material properties conformed to the established anti-corrosion standards[73]. The adhesion of inorganic coatings to metals and other rigid surfaces is typically robust, thereby enhancing the coating's adherence to the substrate and ensuring prolonged protection.

Inorganic zinc-rich coatings represent a high-performance anticorrosive solution primarily composed of zinc powder and inorganic binders, such as silicates and phosphates. These coatings function through the sacrificial anode protection method, offering notable durability, high-temperature resistance, environmental sustainability, and excellent adhesion properties. Researchers in China have undertaken comprehensive investigations into the application processes of inorganic zinc-rich coatings, aiming to enhance both construction efficiency and coating performance. For instance, the inorganic zinc-rich coatings developed by the Key Laboratory of Special Inorganic Coatings at the Chinese Academy of Sciences have been utilized as sacrificial anodes and have found extensive application in marine platforms, ships, and other related structures[74]. Yang Pengfei et al. developed an alcohol-soluble, inorganic zinc-rich anti-slip coating aimed at enhancing the service life of steel structures. This was achieved through the incorporation of a specific dosage of anti-slip fillers and additives into a distinctive inorganic zinc-rich resin[75]. Li Weili et al. characterized the resin obtained through Fourier Transform Infrared Spectroscopy (FTIR) and X-ray Diffraction (XRD). They analyzed the thermomechanical properties of the coatings using techniques such as Thermogravimetric Analysis (TG) and Differential Scanning Calorimetry (DSC) in order to develop coatings that exhibit straightforward preparation methods and enhanced performance[76]. Wang Lin et al. synthesized alcohol-soluble acrylic resins through free radical polymerization and subsequently combined these resins with silica sols to achieve physical cold-splicing, resulting in the formation of alcohol-soluble organic/inorganic composite resins[77]. Subrahmanya Shreepathi and Priyansh Bajaj conducted experiments utilizing electrochemical impedance spectroscopy, which demonstrated that coatings containing 40% exhibited significant corrosion protection. This effectiveness can be primarily attributed to the barrier protection mechanism inherent in the epoxy resin[78]. Silicate coatings, primarily composed of silicate materials, are classified as inorganic coatings. These coatings exhibit exceptional heat resistance, chemical resistance, and environmental protection properties, making them suitable for applications in high-temperature environments, as well as in the presence of water and chemical reagents, among other challenging conditions. The stability of the coating at elevated temperatures, coupled with its remarkable resistance to a broad spectrum of corrosive media, underscores its utility. Furthermore, the coating is non-toxic and odorless, utilizing water as the dispersing medium, which minimizes its environmental impact. A study conducted by Long Weiyun and Professor Gu Xiaoyu focused on the preparation and performance analysis of high-performance silicate-based intumescent fireproof coatings. Their findings indicate that the incorporation of various additives can significantly enhance the properties of silicate fireproof coatings[79]. Wei Xiangyang incorporated an organic film-forming base and corrosion-inhibiting materials into conventional waterborne inorganic zinc-rich coatings. This modification addressed the limitations of standard waterborne inorganic zinc-rich coatings, which are significantly influenced by the construction environment. The enhancements resulted in improved adhesion, densification, aging resistance, and slip resistance of the coating film[80]. Sandrine Dalbin et al. concluded that the corrosion resistance of coatings is significantly influenced by the composition of the deposition solution. This conclusion was drawn from a comparative analysis of the visual effects of various coating formulations following salt spray testing. The experimental formulations identified in their study are extensively utilized in the protection of steel against corrosion[81]. Jaekyu Min et al. conducted an investigation on silicate coatings utilizing kinetic potential polarization curves. Their findings indicated that a protective layer approximately 100 nm in thickness was established on the zinc substrate. This layer effectively inhibited the cathodic reaction of zinc, thereby enhancing its corrosion resistance[82].

Despite ongoing technological advancements by enterprises, protective coatings continue to exhibit numerous deficiencies. For instance, epoxy powder and its associated anti-corrosion layers encounter quality issues, with the primary nonconformities pertaining to thermal properties, density, and particle size distribution. Notably, thermal property indicators, such as heat release during reaction and glass transition temperature, are critical determinants of coating performance. The inadequate performance of adhesive tapes is evidenced by their water absorption and peel strength; elevated water absorption levels can lead to performance failures. Issues with liquid coatings predominantly arise in the post-film formation phase, particularly concerning adhesion and impact resistance. The performance deficiencies of heat-shrinkable tapes (sleeves) are primarily associated with tensile yield strength and oxidation induction period. The former may be linked to the molecular structure of the material, while failure in the oxidation induction period suggests insufficient thermal and oxygen stability of the material[83]. Balgude et al. conducted a study to examine the impact of varying concentrations of modified silane on coating performance. Their findings indicate that a modified silane content of 20% yields superior corrosion protection; however, this concentration is associated with suboptimal adhesion properties[84]. Furthermore, there are numerous instances of the combination of organic and inorganic coatings in China. For example, the offshore platform utilizes the organic-inorganic composite polymer coagulant PE-XN22S, which is synthesized from nano-organic flocculants. This formulation incorporates various polymers that serve the functions of complexation and thickening, thereby enhancing the sedimentation capabilities of the chemically modified surface, which effectively contributes to corrosion protection[85]. Offshore platforms frequently employ inorganic zinc-rich coatings in combination with silicone resin and epoxy resin coatings to achieve superior adhesion and effective resistance to elevated temperatures, high salinity, ultraviolet radiation, and other environmental factors.

4. Conclusion

With the rapid development of the marine economy, the construction and maintenance of offshore platforms have emerged as significant concerns. In particular, the anticorrosion treatment of these platforms is critical during both construction and maintenance phases. Research into corrosion mechanisms, the exploration of anticorrosion technologies, and the development of anticorrosion coatings have collectively advanced the field of anticorrosion research and treatment for offshore platforms. This progress is essential for maximizing the platforms' capabilities and ensuring safe production and operation. This paper begins by highlighting the importance of addressing corrosion in offshore platforms and the associated protective technologies. It delves into the corrosion challenges encountered by these platforms in marine environments, systematically analyzing the various types of corrosion, their underlying causes, and their implications for the structural integrity of the platforms. By examining the corrosion characteristics specific to different regions, the paper proposes corresponding protective measures. These measures encompass a range of strategies, including material selection, electrochemical protection methods, and coating protection. In terms of material selection, the paper emphasizes the need to consider both corrosion resistance and mechanical strength comprehensively. The electrochemical protection methods, particularly the sacrificial anode method and applied current cathodic protection, are demonstrated to be effective means of mitigating corrosion. Furthermore, the combined application of organic and inorganic coatings is presented as a holistic solution for corrosion protection in offshore platforms.

Despite the considerable advancements achieved in corrosion protection technology for offshore platforms, numerous challenges persist. The intricate nature of the corrosive environment presents a significant obstacle, as the corrosion characteristics differ across various zones, including the atmospheric zone, splash zone, tidal zone, fully submerged zone, and seabed sediment zone. This variability imposes heightened demands on protective measures. Moreover, although the introduction of new materials and sophisticated anti-corrosion technologies—such as stainless steel, titanium alloys, and specially treated corrosion-resistant alloys, in addition to electrochemical protection methods and coating technologies—has markedly enhanced the durability of offshore platforms, the associated high costs remain a substantial limitation. This issue is particularly pronounced in marine environments characterized by high humidity and elevated temperatures, where traditional steel materials often fail to meet operational requirements. The adoption of new materials inevitably exacerbates the economic burden. Furthermore, the implementation of these anti-corrosion technologies necessitates regular inspection and maintenance in practical applications, including anode replacement in electrochemical protection systems and repairs of protective coatings, to maintain their efficacy. This requirement further escalates operational costs and complicates management. Consequently, identifying strategies to mitigate costs and maintenance challenges while ensuring the effectiveness of anti-corrosion measures represents a critical avenue for the future advancement of corrosion protection technology for offshore platforms.

The ongoing emergence of novel materials and technologies, including the application of nanotechnology and bioengineering, presents new developmental opportunities for anti-corrosion technology. Furthermore, as the effects of global climate change become increasingly pronounced, the integration of environmental protection principles into anti-corrosion technology to promote sustainable development is expected to be a central focus of future research.

Table 2. Summary of research and technology overview on offshore corrosion protection.

Objects	***Classifications***	***Descriptions***
Corrosion Types	From the Cause Perspective	Electrochemical corrosion，microbial corrosion, and stress corrosion.
	From the Phenomenon	Localized corrosion and uniform corrosion.

	Perspective	
Material Selection		Stainless steel, titanium alloy, or special corrosion-resistant alloy materials are commonly used.
Various Anti-corrosion Techniques	Electrochemical Protection Methods	Impressed current protection method (suitable for large -scale structure anti-corrosion), sacrificial anode method (greatly affected by temperature)
	Coating Protection Methods	Organic coatings and inorganic coatings.

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