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A Case Study on the Corrosion of an Aging Jack-Up Drilling Rig

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Abstract: Corrosion costs the Oil & Gas Industry billions of pounds annually, primarily due to environmental factors such as high salinity, temperature fluctuations, and humidity in marine environments. Mobile Offshore Drilling Units (MODUs), especially jack-up rigs, are particularly susceptible to these dangers. This paper examines the impact of cold stacking on aging jack-up rigs and highlights how the absence of an adequate corrosion control system can accelerate structural deterioration. Our findings show that repair costs following cold stacking can far exceed the costs associated with maintaining rigs in a warm-stacked state. Preload tanks are critical areas prone to degradation due to microbiologically influenced corrosion (MIC) and inadequate preservation practices. Furthermore, although high-strength steels are frequently utilized in the construction of jack-up rigs due to their durability, we illustrate that, in the absence of meticulously devised preventative measures, these steels are susceptible to considerable corrosion, resulting in substantial repair expenses and diminished operational lifespans. This study highlights the significance of proactive corrosion control measures in maintaining the long-term structural integrity and cost-effectiveness of offshore drilling units.

Keywords: corrosion; jack-up; offshore drilling; management; oil and gas

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1. Introduction

Corrosion in marine structures is mostly induced by electrochemical (electricity and chemical) processes, notably anodic dissolution. The pace and characteristics of corrosion processes, including pitting, crevice corrosion, and microbiologically influenced corrosion (MIC), are regulated by variations in salinity, oxygen concentration, and temperature. Prior research [1] has shown that chloride ions expedite localized corrosion, especially in high-strength steel elements. This study seeks to enhance existing knowledge by examining corrosion development in an aging jack-up rig, utilizing a blend of visual examination, non-destructive testing (NDT), and the quantitative evaluation of corrosion rates. The results enhance the scientific comprehension of corrosion mitigation measures for offshore drilling units. This research examines the corrosion issues encountered by a particular jack-up drilling rig, with conclusions that have wider relevance for offshore structures in marine environments. The processes of pitting, crevice corrosion, and microbiologically influenced corrosion (MIC) are commonly encountered in analogous situations, underscoring the general applicability of the proposed mitigation measures. This work seeks to enhance the knowledge and prevention of maritime corrosion by integrating real case observations with theoretical insights, providing essential guidance for researchers and industry experts alike.

Marine corrosion is influenced by factors such as salinity, temperature, oxygen concentration, and biofouling and could be of different types, which are summarized as follows:

- Uniform Corrosion: Occurs evenly across a metal surface, facilitated by the consistent presence of oxygen and saltwater.
- Pitting Corrosion: This localized form results in small pits or holes, often exacerbated by chlorides that breach the protective passive layer on metals like stainless steel.
- Galvanic Corrosion: Occurs when two dissimilar metals are electrically connected in a conductive environment, leading to more anodic metal corroding faster.
- Crevice Corrosion: This happens in confined spaces where stagnant seawater leads to oxygen depletion and an aggressive localized attack.
- Microbiologically Influenced Corrosion (MIC): Involves the action of microorganisms that produce corrosive by-products.

The environmental influences on corrosion rates include

- Salinity and Chloride Ions: Chlorides show great aggressiveness that helps protective oxide coatings on metals be broken down [2]. More notable metal deterioration results from the increased chloride ion concentration increasing the corrosion process and rate of cathodic migration [3].
- Temperature: Rising temperatures speed up oxygen movement and electrochemical reactions, hence aggravating corrosion rates. Temperature variations considerably modify the microbial community structure in production fluids, thereby influencing the biocorrosion of carbon steel under anaerobic circumstances. Furthermore, temperature variations can significantly influence corrosion processes, especially microbiologically influenced corrosion (MIC) [4].
- Oxygen Concentration: In both pitting and uniform corrosion, theoxygen level is vital. Anaerobic conditions produced in oxygen-deficient settings improve the activity of sulfate-reducing bacteria (SRB), which are main causes of microbiologically induced corrosion (MIC). These hypoxic-loving bacteria cause biofilm to develop and hasten corrosion rates [5].

The marine environment could be classified into several zones, each with distinct corrosion characteristics:

- Atmospheric Zone: Exposed areas subject to sea spray and periodic wetting. Corrosion here is influenced by humidity and salt deposition.
- Splash Zone: Experiences frequent wet–dry cycles, leading to severe corrosion due to repeated exposure to oxygen and chlorides.
- Tidal Zone: Alternate between submersion and exposure, promoting uniform and pitting corrosion.
- Submerged Zone: Constant immersion leads to consistent but generally lower corrosion rates than the splash zone. Oxygen availability and microbial activity influence the corrosion type.
- Seafloor and Sediment Interface: Low oxygen and microbial-rich environments often lead to MIC.

The application of specialized marine coatings provides a physical barrier against water and oxygen. Epoxy-, polyurethane-, and zinc-rich coatings are extensively used for their durability and corrosion resistance in marine conditions [6]. Additionally, sacrificial anode and impressed current cathodic protection (ICCP) methods provide a reliable defense against galvanic corrosion in offshore drilling structures. Priced et al. discussed the importance of integrating protective coating systems with cathodic protection to safeguard offshore wind structures against corrosion and fatigue damage. The study emphasized that such combined systems are essential for maintaining the structural integrity and extending the service life of these installations [7]. The choice of corrosion-resistant alloys, such as stainless steel (grades 316 and duplex stainless steels) and copper–nickel alloys, has been shown to offer enhanced durability. The incorporation of alloying elements such as molybdenum and chromium has been shown to enhance resistance against pitting and crevice corrosion in stainless steels [8,9]. Innovative coating technologies, such as self-healing and anti-fouling coatings, have been developed to enhance the durability of offshore structures [10]. Advances in microbiology and biotechnology have allowed for the better understanding and control of MIC. Innovative approaches include biocide treatments and the genetic modification of materials to resist biofouling.

Jack-up rigs, primarily used for offshore drilling in waters less than 150 m deep, also function as offshore living quarters and production facilities. Drilling jack-ups are especially prone to corrosion due to their operating environment. The hull's bottom periodically contacts seawater, exposing it to cyclic wet and dry conditions [11]. Drilling rigs operate in highly corrosive environments, leading to significant structural and operational challenges. Corrosion, exacerbated by environmental exposure and harsh operating conditions, impairs equipment performance, shortens lifespans, and increases maintenance costs. As mentioned above, drilling rigs are subject to various forms of corrosion due to their complex structure and exposure to different environments. According to studies by Ahmed et al. [12], uniform corrosion is most commonly observed on external steel surfaces that lack protective coatings. Chlorides in seawater promote pitting, particularly on stainless steel components. Research by Chen et al. [13] demonstrates that pitting can penetrate deeply into the metal, leading to localized failure. Zhang and Huang [14] highlight the role of limited oxygen diffusion in exacerbating crevice corrosion. The study by Patel and Brown [15] shows that galvanic corrosion preferentially corrodes the anodic metal when these metals are electrically connected in a conductive medium like seawater. Miller and Thompson [16] found that MIC can lead to rapid corrosion in zones with prevalent anaerobic conditions.

Various environmental and operational factors magnify the corrosive nature of drilling rigs. Roberts and Lee [17] established that salinity, coupled with high humidity, amplifies the rate of metal oxidation. Temperature fluctuations accelerate metal deterioration, as outlined by Carter et al. [18]. Mechanical stress combined with corrosive exposure contributes to corrosion fatigue. Zhang and Smith [19] analyzed how repetitive loading in conjunction with corrosive attack reduces the structural integrity of drilling components, leading to premature failure.

The interaction between drilling fluids and metal surfaces can exacerbate corrosion. Depending on the composition of the drilling fluids (water-based, oil-based, or synthetic), they can either inhibit or accelerate corrosion processes [20]. Different zones on a drilling rig experience varying degrees of corrosion. The atmospheric zone of rigs, while not constantly submerged, is affected by sea spray and airborne chlorides, resulting in moderate to severe uniform corrosion. The splash zone experiences the harshest conditions due to constant wet–dry cycling and oxygen-rich spray, causing accelerated corrosion. Research by Smith and Peters [19] highlights this zone as one of the most challenging areas to protect. The constant submersion of subsea components exposes them to lower but persistent levels of corrosion. Factors such as water flow and the presence of biofouling organisms influence the corrosion rate. Subsurface and sediment zone areas can be prone to MIC due to reduced oxygen levels and high microbial activity. Johnson and Wu [21] identified these zones as hotspots for rapid corrosion under biofilms.

Various strategies are employed to prevent or slow down corrosion on drilling rigs. Protective coatings are essential for mitigating corrosion. Liu and Sanders [19] emphasise that CP effectively protects submerged metallic structures, provided it is maintained properly. Using corrosion-resistant alloys like stainless steel (e.g., duplex and super-duplex grades) and titanium has proven effective for high-risk areas. Implementing routine inspections using NDT techniques helps in the early detection of corrosion damage. Advanced sensor technologies enable the real-time monitoring of corrosion potential. Adding inhibitors to drilling fluids and seawater systems can reduce corrosion rates. Kim and Patel [22] found that environmentally friendly inhibitors, such as plant-based compounds, promise to mitigate corrosion without harming marine ecosystems. Eco-friendly inhibitors serve as a viable alternative for mitigating corrosion in marine environments owing to their biodegradable and non-toxic characteristics. Unlike conventional inhibitors that frequently incorporate toxic heavy metals or phosphates, these inhibitors reduce environmental hazards while providing equivalent or enhanced efficacy in corrosion prevention. Recent studies show that by forming durable, protective coatings on metal surfaces, which make them fit for sustainable use in offshore projects, plant-derived inhibitors like tannins and alkaloids can effectively reduce corrosion.

Recent advances in technology have led to new ways to combat corrosion. Self-healing and nanocomposite coatings that release protective agents when damaged are being developed. Specifically, self-healing coatings are proving effective in mitigating corrosion in high-risk areas such as the splash zone. Still at the experimental stage, these coatings have not found much application in the offshore industry. White et al. [23] highlighted these coatings as a breakthrough in extending the service life of drilling structures. Research into microbial management has led to the use of biocides and biofilm-resistant materials to counteract MIC. The deployment of IoT-based sensors on rigs for real-time data collection on corrosion parameters has revolutionized maintenance strategies. Modern technologies provide improved corrosion control integrating IoT and smart materials as well. IoT-enabled sensors provide the real-time monitoring of vital components including temperature, salinity, and humidity, thereby providing actionable data for foreseeing and reducing corrosion risks. These sensors may be included in remote monitoring systems, diminishing the necessity for regular physical checks. Moreover, intelligent coatings, including self-repairing polymers and nanostructured materials, can autonomously mend small damage or release corrosion inhibitors in reaction to environmental stimuli. It is recommended to implement IoT-based sensor networks in high-risk areas, such as splash zones and pre-load tanks, and apply smart coatings on important structural components to improve durability. The study by Gomez and Lin [24] showcased how predictive analytics can preemptively address areas prone to severe corrosion.

In drilling rigs, the top of the hull and equipment are subject to the sea's atmospheric conditions (e.g., salty air) and other pollutants. Most of the legs and spud cans are immersed in water, which, again, would also promote corrosion. Pitting corrosion may also be seen in the Splash Zone [25]. Hydrogen Cracking (heat-affected zone or weld metal) is also known to be a problem with some high-strength steels used in the construction of jack-ups, particularly in areas adjacent to welds where increased hardness and residual stresses may exist [26].

This work offers a distinctive examination of corrosion evaluation in a cold-stacked jack-up drilling rig, a strategy employed to save operational expenses during periods of less demand, which has garnered scant attention in the existing literature. This study analyzes the degradation patterns and causes of cold-stacked jack-up rigs, offering new insights into how preservation measures might reduce long-term dangers. Furthermore, we recommend a focused preservation planning strategy that corresponds with industrial requirements and identifies deficiencies in current rules. Through the integration of visual inspection and NDT, we pinpoint crucial locations susceptible to corrosion and illustrate how the improper management of cold stacking can result in substantial structural deterioration. Cold stacking refers to the practice of shutting down a rig with minimal crew and maintenance, making it susceptible to corrosion. In contrast to previous studies that examine broad corrosion processes, our research explicitly links cold stacking circumstances to observed corrosion patterns and suggests a specific preservation method. These findings offer significant insights into cost-efficient maintenance strategies, possibly decreasing repair expenses and prolonging the operating lifespan of offshore structures. This work improves the present knowledge by

- Acknowledging the higher sensitivity of cold-stacked rigs to localized corrosion events including pitting and microbiologically driven corrosion (MIC).
- Showing how particular preservation techniques, like the optimization of cathodic protection and frequent NDT inspections, could extend the operating lifetime of these towers.
- Providing actionable recommendations for future regulatory advancements to more effectively mitigate corrosion risks during cold stacking.

These contributions connect theoretical corrosion research with practical applications, establishing a basis for enhanced industrial practices.

This case study examines a singular jack-up drilling rig, detailing its corrosion and preservation difficulties throughout time. The images and information supplied encompass several inspection and maintenance initiatives undertaken between 2012 and 2018, illustrating the rig's lifespan assessment and the enduring effects of conservation methods. This historical information is presented to offer thorough knowledge of the rig's structural performance under different situations.

2. Problem Overview: Corrosion Challenges in Jack-Ups

A jack-up is a Mobile Offshore Drilling Unit (MODU) and consists of three main components, which are the Hull, Legs, and Spud cans, as well as many other pieces of equipment, as shown in Figure 1.

Figure 1. Components of a jack-up drilling rig.

The Hull is a watertight structure on which the Cantilever and Jacking System, living quarters, helideck, and equipment are housed. The leg and spud cans are steel structures that support the hull when it is elevated. The spud cans of the jack-up are footings that penetrate the seabed to provide adequate bearing and lateral stability. The jacking system is a mechanism that can lift or lower the hull of a jack-up, the most common of which is a Rack and Pinion system.

The jack-up must settle on the seabed soil; therefore, there are a few preload tanks within the hull. Different designs have different tank arrangements, and Figure 2 shows the general arrangement of the pre-load tanks on the jack-up rigs investigated within our research. During the pre-load, seawater is pumped into these tanks until a full settlement on the seabed is achieved, and then the preload water is dumped overboard.

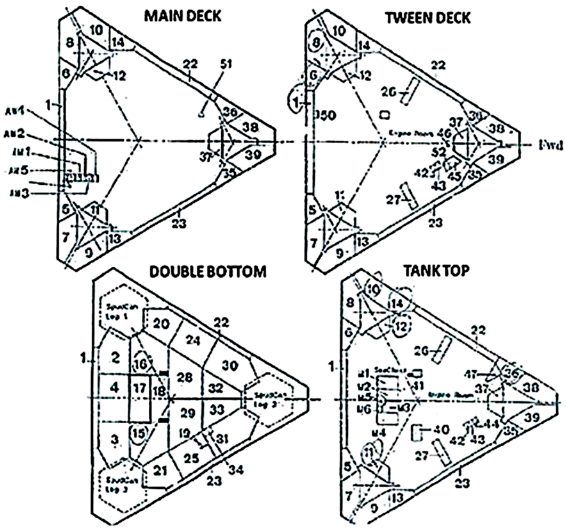

Figure 2. The arrangement of pre-load tanks in our researched jack-ups.

The original jack-up structures were fabricated using mild Carbon Steel, which is susceptible to pitting and crevice corrosion. Many manufacturers are currently using Duplex and higher-strength steel. However, given the operating environment, there is still a need for corrosion management systems.

A situation when the rig is not operating but is kept with engines running and lights on, with less crew, is known as warm stacking. The rig would be ready to be operational on short notice. In contrast, cold stacking is when the engines are shut down, with only temporary lighting necessary for conducting checks. Only a few security staff would be present, hence the rig being idle, i.e., there is no expectation of operation within a short period. The cost-effectiveness of warm stacking compared to cold stacking is contingent upon several factors, including preservation methods and longevity. Although warm stacking entails higher initial operational costs, insufficient preservation during cold stacking may lead to substantial repair expenditures. Additional cost–benefit assessments are necessary to offer conclusive information.

While this study does not include a detailed cost analysis, industry data suggest that steel renewal and coating repairs for similar offshore structures can range from USD 300,000 to USD 600,000 depending on the extent of damage. Preservation during cold stacking, such as routine inspections and anode replacement, is typically more cost-effective, with annual maintenance costs estimated at USD 150,000–200,000. A detailed cost–benefit analysis indicates that proactive corrosion prevention strategies significantly reduce long-term maintenance expenses. While cold stacking appears more economical in the short term, the lack of maintenance leads to accelerated degradation, often requiring steel renewal and coating repairs costing USD 300,000–600,000 per overhaul.

Comparatively, investing in regular NDT, optimized cathodic protection, and high-performance coatings can extend the operational life of the structure by 5–10 years, reducing total repair costs by up to 40% over the rig's lifespan.

The cost of cold and warm stacking can be summarized as follows:

1. Cold Stacking Costs:
    - Annual Maintenance Costs: Cold stacking can save approximately USD 4.5 million per year per vessel, including about USD 500,000 in regulatory docking fees [27]
    - Reactivation Costs: Reactivating a cold-stacked rig can range from USD 25 million to USD 70 million, with about 50% of the cost attributed to commissioning major equipment and the remainder covering ancillary services like the crew, shipyard, and logistics [28].
2. Warm Stacking Costs:
    - Daily Costs: Warm stacking a rig costs approximately USD 40,000 per day, equating to about USD 14.6 million annually [29].

These findings highlight that preventive maintenance, though requiring upfront investment, is more cost-effective in the long run than allowing structures to deteriorate without intervention.

Including such cost factors in future projects would help to give more complete knowledge of the financial consequences of corrosion control measures.

Minimizing long-term damage during cold stacking requires careful preservation planning. Key practical measures include the following:

Regular visual and NDT inspections help to identify early corrosion or mechanical damage.

- Optimized Cathodic Protection: Verify the regular efficiency of sacrificial anodes or impressed current systems through accurate installation and monitoring.
- Track humidity, temperature, and salinity degrees to evaluate environmental hazards and modify preservation plans.
- Particularly in sensitive places like the splash zone and ballast tanks, apply and maintain high-performance coatings meant for maritime situations.
- Lubricate and guard important moving components, including jacking systems, to avert operational failure upon reactivation.

These processes establish a coherent framework for efficient preservation during cold stacking and conform to best standards in offshore asset management.

Efficient preservation measures can reduce the hazards of corrosion during cold stacking and prolong the operating lifespan of offshore structures. The next suggested action plans and quantifiable benchmarks are the following:

Routine Monitoring Using IoT Sensors: Install IoT-enabled temperature, salinity, and humidity sensors. By as much as thirty percent, real-time monitoring helps to minimize inspection costs and supports quick actions.

- Recent studies show that using self-healing polymer coatings capable of independently repairing minor damage will help to reduce maintenance frequency by 40%.
- Enhanced Cathodic Protection Systems: Consistently oversee and modify sacrificial anodes or impressed current systems. This can reduce corrosion rates in submerged areas by as much as 50% when tuned using real-time data.
- Environmental Adaptations: Employ desiccant devices in pre-load tanks to regulate humidity and mitigate microbiologically influenced corrosion (MIC), which has demonstrated a 70% reduction in microbial activity in controlled settings.

- Pragmatic Obstacles include the following:
    - ➢ Expense: The first implementation of IoT systems and sophisticated coatings may elevate initial expenditures, necessitating a thorough cost–benefit evaluation.
    - ➢ Integration: Retrofitting antiquated rigs with IoT technologies and advanced materials may provide logistical difficulties, especially in inaccessible locations.
    - ➢ Data Management: Managing substantial quantities of real-time data needs resilient infrastructure and specialized knowledge.

Confronting these problems necessitates a gradual adoption, the prioritization of high-risk regions, and the utilization of current maintenance schedules to effectively incorporate new technologies.

3. Fundamentals of Corrosion Mechanisms

Corrosion is an important issue in the integrity of jack-up drilling rigs, especially with the aging of the jack-up [30]. Many jack-ups are operating beyond their design life, and therefore, corrosion must be managed [31].

Because of its frequent wetting and drying, which aggravates corrosion, the splash zone poses serious problems. Recent advances in coating technologies—including graphene-enhanced coatings and fluoropolymers—have shown remarkable resistance under very demanding conditions. Compared to traditional epoxy-based solutions, these new coatings provide enhanced durability and adhesion, therefore greatly reducing corrosion rates. Including these innovations into further preservation projects will help to more successfully handle issues with splash zones.

Figure 3 shows that corrosion rates vary greatly throughout different zones of the structure; the splash zone shows the highest rates because of its exposure to cycle wetting and drying conditions.

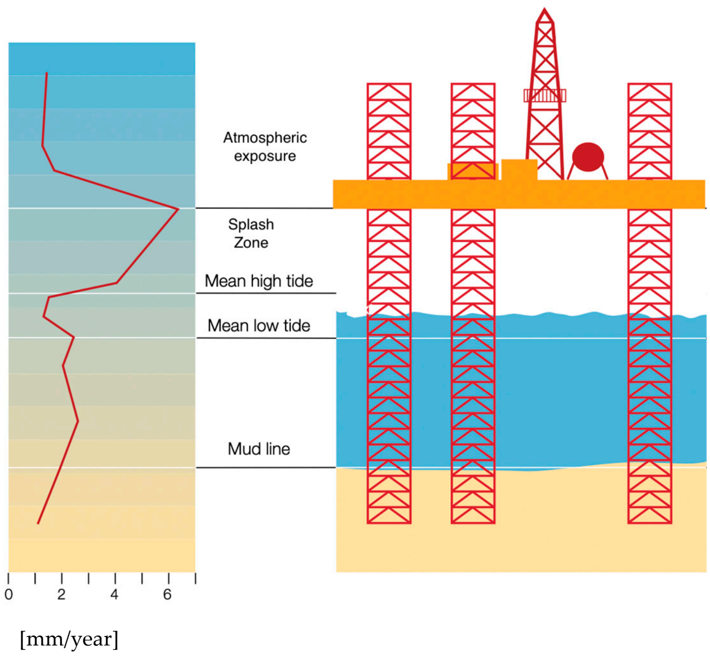

Figure 3. Observed corrosion rates in different zones, based on original inspection data from this study [32].

Table 1 ranks different structural zones based on their corrosion severity, structural importance, and ease of inspection. The splash zone and ballast tanks are at high risk due to severe cyclic wetting/drying and microbiologically influenced corrosion (MIC). While legs and spud cans experience lower corrosion rates, their critical structural role makes them a high-priority area for maintenance.

Table 1. Corrosion Risk Matrix for Structural Zones of a Jack-Up Rig.

Structural Zone	Corrosion Rate (mm/Year)	Structural Importance	Inspection Difficulty	Overall Risk Level
Splash Zone	0.3–0.5 mm/year	High	Medium	High
Ballast Tanks	0.2–0.4 mm/year	High	High	High
Hull Perimeter	0.1–0.3 mm/year	Medium	Low	Medium
Legs and Spud Cans	0.05–0.2 mm/year	Very High	High	High
Deck and Superstructure	<0.1 mm/year	Low	Low	Low

Based on the corrosion risk matrix, inspection and mitigation efforts should follow a tiered risk-based approach:

1. High-Risk Areas (Splash Zone, Ballast Tanks, Legs and Spud Cans)
   - Inspection Frequency: Every 6–12 months using ultrasonic thickness (UT) measurements and non-destructive testing (NDT).
   - Mitigation: Apply high-performance coatings, conduct cathodic protection system checks, and install real-time corrosion sensors.
2. Medium-Risk Areas (Hull Perimeter)
   - Inspection Frequency: Every 12–24 months with routine visual inspections.
   - Mitigation: Reapply coatings every 5 years, monitor humidity/salinity levels.
3. Low-Risk Areas (Deck and Superstructure)
   - Inspection Frequency: Every 3–5 years.
   - Mitigation: Basic preventative coatings and environmental monitoring.

DNV-GL [33] divides corrosion into four categories:

- General: Where uniform reductions in the material are found.
- Pitting: Randomly scattered corrosion spots/areas with local material reductions.
- Grooving: Local line material losses normally adjacent to welding joints, along with abutting stiffeners and at stiffeners, plate butts, or seams.
- Edges: Local material wastage at the free edges of plates and stiffeners.

The two principal methods of controlling corrosion are Coating and Cathodic Protection.

Protective coatings are used for different parts of a jack-up. In applying such coatings, the anticipated duration of the protection, ease of application, cost-effectiveness, abrasion resistance, resistance to corrosion chemicals and water, heat resistance, durability, and environmental conditions need to be considered [34].

There are two methods of cathodic protection, namely, Impressed Current Cathodic Protection and Sacrificial Anodes [35].

The cathodic protection system can be visually inspected by an ROV, checking the size of the anodes, as well as ensuring that all anodes are in place. The length and breadth can also be measured if a more rigorous inspection is needed or when deciding if the anodes have to be replaced.

The rate of corrosion varies in different parts of a jack-up, as the bottom of the hull, legs, and spud cans are in contact with seawater, whilst other conditions like carbon dioxide (CO_2), hydrogen sulfide (H_2S), temperature, and pH might contribute to corrosion on other parts of the rig. Hydrogen can also attack high-strength steels, particularly adjacent to welds where increased hardness and residual stresses might exist [36]. A thorough investigation of Hydrogen cracking was made specifically on the legs and spud cans of jack-up drilling rigs [11]. It was found that

1. Cracking occurred at the intersection between the leg chord and the spud can top plate within the heat-affected zone of the high-strength material.
2. Extensive cracking was found inside the spud cans of a rig operating in Argentina.
3. Hydrogen sulfide (H_2S) was present in the cracked zones. Hydrogen-assisted cracking, which could occur without H_2S, is likely to be present.
4. A further rig was found to have severe cracking within the spud cans in the same year, and the cracking also extended to the external welds between the leg chords and the spud can's top plates. A later survey showed that the cracking had mainly occurred where the paint coating had been removed to allow for underwater inspection or where the coating had deteriorated inside the spud cans. It was then confirmed that the cracking here was more due to hydrogen than fatigue.

Effective management systems as a whole, as well as corrosion management planning, are thus vital for jack-ups to reduce maintenance costs. Corrosion management is part of the overall management system, which is concerned with the development, implementation, review and maintenance of the corrosion policy [37].

4. Case Study

The case studied was constructed in 1985 with a maximum water depth of 328 ft, shown in Figure 4. The rig was cold stacked for a year and the initial survey showed that remedial work due to corrosion was required to reactivate the rig. Just one year after the rehabilitation, significant corrosion damage was noted, which called for more repairs. This review reveals possible contributing reasons, including inadequate surface preparation before the protective coatings are applied, poor coating choice for high-salinity and splash zone conditions, or application problems including unequal coating thickness. The rapid corrosion observed just one year after the overhaul can be attributed to several key factors, as follows:

1. Inadequate Surface Preparation: If the surface was not properly cleaned and prepared before applying protective coatings, poor adhesion could have led to premature coating failure.
2. Coating Selection or Application Issues: The coatings may not have been suitable for the high-salinity splash zone conditions, or they may have been applied unevenly, leading to early degradation.
3. Lack of Post-Overhaul Maintenance: Routine inspections and maintenance may not have been conducted effectively, allowing corrosion to progress undetected.
4. Environmental Factors: High humidity, fluctuating temperatures, and microbiologically influenced corrosion (MIC) in ballast tanks and splash zones likely accelerated material degradation.

These results imply that early deterioration can be avoided by more rigorous quality control throughout building operations. Although particular ultrasonic thickness (UT) data are lacking for this work, the observed corrosion processes and zones of degradation fit generally accepted patterns in the literature. For instance, investigations on the splash zone have revealed that driven by oxygen-rich conditions and periodic wetting and drying, it usually shows corrosion rates of 0.3–0.5 mm/year. These results set a standard for knowledge of the degree of material loss in this area.

Figure 4. The case study jack-up before sailing to the shipyard for repair.

Structural components of the jack-up rig were evaluated using NDT methods. Based on the time-of- flight concept of high-frequency sound waves, ultrasonic testing (UT) was used to evaluate the thickness loss resulting from corrosion. Using the ideas of magnetic flux leakage in ferromagnetic materials, magnetic particle inspection (MPI) was also performed to find surface and near-surface defects. Environmental data analysis complimented these techniques by helping to link corrosion rates with exposure circumstances, therefore offering a data-driven means of structural health monitoring. Consequently, the methodology consisted of the following actions:

- Visual Inspection: Initial structural evaluation looking for obvious corrosion indicators like material loss, pitting, and coating deterioration.
- While Magnetic Particle Inspection (MPI) was used to identify surface cracks and faults in welds and joints, Ultrasonic testing was utilized to gauge material thickness [34].
- Following DNV.GL criteria for structural integrity evaluation, corrosion-prone zones were classified according to degree.
- Documentation and Recommendations: Based on the results, a color-coded damage map was created to rank repairs and mitigating ideas were developed.

Visual examination and NDT taken together provide complete knowledge of the structural damage. For example, MPI found cracking in weld joints while UT measurements verified the degree of material loss in the splash zone. These results highlight the necessity of focused preservation techniques like regular inspections and improved cathodic protection to help to reduce the hazards revealed in this case study. Methods of NDT gave important new perspectives on the jack-up rig's structural integrity. NDT does, however, have several inherent limits, including difficulties reaching intricate structural sections and the possibility of false negatives brought on by surface contamination or inadequate calibration. To guarantee a more complete evaluation, future research should take into account combining NDT with complementary technologies as improved imaging approaches or destructive testing.

Based on the results of the two surveys, it was decided to renew the protective coating and paints, add new Cathodic protection, as well as replace badly deteriorated components. The work was divided into three parts, namely, the hull, the legs, and the spud cans and the equipment.

The coating systems used in offshore structures typically consist of multi-layer epoxy and polyurethane coatings designed to resist saltwater exposure and mechanical wear. In the case of jack-up rigs, three-coat systems are commonly applied:

1. Primer Layer: Zinc-rich epoxy (50–75 µm) for cathodic protection.
2. Intermediate Coat: High-build epoxy (150–200 µm) for barrier protection.
3. Topcoat: Polyurethane (50–75 µm) for UV and mechanical resistance.

The total dry film thickness (DFT) of these coatings is typically 250–350 µm, depending on the exposure zone. Edge protection is critical since edges and welds are prone to early corrosion due to thinner coatings. To address this, edges were rounded and stripe-coated before the full coating application. Furthermore, welds received extra epoxy layers to prevent premature failure. Hard-to-reach areas, such as spud cans and ballast tanks, require specialized spray or brush application techniques to ensure uniform coverage. These areas were also monitored with coating adhesion tests and ultrasonic thickness measurements post-application.

4.1. Main Deck

The repairs to the main deck comprised a completed steel renewal and repair at nine locations; three applications of coating of the entire main deck; repair to deckhouse structures as per the DNV load line survey, which included some renewal of the steelwork; the renewal of 12 pieces of the tank manhole and six pieces of the blank flange; pipe rack strengthening by partial renewal and repair; and the renewal of all Bollard caps. The repair uncovered substantial corrosion in various regions of the structure, notably in the splash zone and ballast tanks. Key observations encompass the following:

1. Splash Zone: Significant pitting corrosion was noted, presumably resulting from repeated wetting and drying coupled with insufficient coating adherence.
2. Ballast Tanks: Evidence of microbiologically influenced corrosion (MIC) was observed, aggravated by inadequate ventilation and elevated humidity levels.
3. Hull: Uniform corrosion transpired as a result of the deterioration of the protective covering.

Table 2 encapsulates these data, offering a comprehensive critical examination of the impacted locations and possible mechanisms leading to the observed damage.

Table 2. Summary of Corrosion Types and Recommendations by Location.

Location	Corrosion Type	Contributing Factors	Recommendations
Splash Zone	Pitting Corrosion	Cyclic wetting/drying, poor coating adhesion	Improved surface preparation and coating
Ballast Tanks	MIC	High humidity, inadequate ventilation	Enhanced ventilation and monitoring
Hull	Uniform Corrosion	Coating degradation over time	Periodic reapplication of high-performance coatings

Figure 5 illustrates the actual steel replacement on one location of the Hull, respectively.

Figure 5. Steel renewal in place.

4.2. Hull Perimeter

Hydro-blasting of all tanks and repairs as needed. Also, three-coat painting of the entire hull perimeter (Figure 6).

Figure 6. Hull perimeter before and after the protective coating.

- Jack House Wind wall: Removal of old corroded cladding, repair to corroded support beams and C-Channel foundation, and installation of a new wind wall, including new doors.
- Piping: Koomey unit HP tubing, seawater line at storeroom walkway, corroded hammer unions at the drill floor, main engine and compressor cooling lines piping renewed, flushed, and tested, and the drill water and airline from the cantilever to drill floor renewed.
- Hull Bottom Repair: Holes were detected during hull integrity inspection. The steel plate was replaced (Figure 7).

Figure 7. Steel replacement at the Hull's bottom.

- Helideck Structure: Buttering of corroded and pitted areas, with localized repair and painting.
- Legs and spud cans: Figure 8 shows part of the corroded leg.

Figure 8. Corrosion on the legs.

- Living Quarter before and after

The repairs conducted on the living quarters can be seen before and after the repairs and the application of the new coating in Figure 9.

Figure 9. The living quarters.

- Pre-load tanks repair

Most of the pre-load tanks were inspected visually and by NDT. The plates that were worst corroded had to be renewed. The tank was accessed by cutting the perimeter of the hull.

After any repair, a survey was carried out by Class Organization *, and a five-year Class was awarded at the end of repair for the said jack-up.

The principal conclusions of the case study are encapsulated as follows:

- The splash zone exhibited the most elevated corrosion rates, attributed to recurrent wet–dry cycles and significant saline exposure. Significant pitting corrosion led to material loss of up to 6 mm in certain regions.
- Pre-load Tank No. 8 demonstrated significant corrosion attributed to microbiologically influenced corrosion (MIC), requiring comprehensive steel and coating replacements.
- Hull Perimeter: Significant coating deterioration and homogenous corrosion were observed, necessitating steel replacement in many areas due to thickness reduction.
- Localized hydrogen-assisted cracking was detected at weld joints of the legs and spud cans, intensified by residual stresses and coating degradation.

Table 3 provides an overview of the critical areas and their respective damage levels.

Table 3. Overview of critical areas and their damage levels.

	Damage Type	Observations	Recommended Action
Splash Zone	Pitting Corrosion	Material loss up to 6 mm	Steel renewal and re-coating
Pre-load Tank No. 8	Microbiologically Influenced Corrosion (MIC)	Severe corrosion in stiffeners	Steel and coating renewals
Hull Perimeter	Uniform Corrosion	Widespread coating degradation	Steel plate replacement and re-coating
Legs and Spud Cans	Hydrogen-Assisted Cracking	Cracking at weld joints	Weld repairs and anode replacement

5. Concluding Remarks

This practice shows that for any jack-up, there should be a plan based on:

- Corrosion Monitoring
- Corrosion Inhibition

The plan should be regular NDT in conjunction with a visual inspection. When we visited the said jack-up, cold stacked in a UAE Shipyard a year after the repairs, we found there were many parts corroded, including the hull surface, the welded joints, and the legs. Cold stacking is a cost-effective option during periods of inactivity; however, improper preservation can lead to severe corrosion, causing repair costs to outweigh initial savings. Therefore, Preservation Planning should be considered during cold stacking.

The insights derived from this case study furnish concrete solutions for the examined jack-up rig and present a framework for comprehending corrosion dynamics in other offshore structures. This study connects case-specific findings to universal corrosion mechanisms, bridging the divide between real engineering challenges and theoretical developments and enhancing the overall understanding in marine corrosion research. Subsequent studies should investigate the use of corrosion prediction modeling methodologies, including finite element analysis (FEA) and empirical corrosion rate equations, to anticipate long-term structural degradation. Utilizing sensor-based monitoring and AI-driven predictive maintenance, offshore operators may proactively mitigate corrosion risks, therefore decreasing repair expenses and prolonging the operational lifespan of aged rigs. The results highlight that inadequate surface preparation and insufficient protective measures lead to early corrosion, as seen in this instance. Implementing effective quality assurance during restorations, together with continuous monitoring, can reduce these hazards and enhance the long-term performance of offshore buildings.

Subsequent studies ought to include ultrasonic thickness assessments and cost–benefit studies to evaluate material degradation and repair costs. These data would enhance the qualitative insights in our study, providing a more solid foundation for formulating targeted corrosion management measures. This work enhances the comprehension of corrosion control in cold-stacked jack-up rigs, a subject that has garnered less focus in current literature. By correlating empirical facts with theoretical ideas, we provide a basis for effective preservation measures that minimize maintenance expenses and prolong the operational lifespan of offshore buildings. Future research should concentrate on measuring the enduring advantages of these tactics and incorporating them into revised industry recommendations to correspond with changing environmental and economic problems.

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