

Corrosion Detection Techniques for Asset Integrity and Maintenance in the Oil and Gas Industry: A Review

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Abstract: Corrosion detection is essential for maintaining infrastructure safety, reliability, and longevity, particularly in industries such as oil and gas, where harsh environmental conditions accelerate material degradation. Corrosion in this industry affects the structural integrity of pipelines and increases life cycle costs. Carbon steel, a commonly used material, is highly susceptible to corrosion due to extreme operational conditions like high pressure, temperature fluctuations, and exposure to corrosive elements such as CO₂, H₂S, and chlorides. The extensive network of pipelines and remote locations make real-time corrosion detection challenging, as traditional inspection methods often prove insufficient, particularly for internal monitoring. Deep gas wells add another layer of difficulty, requiring reliable wireless communication for data acquisition. However, challenges persist in effectively detecting corrosion, especially in large, complex systems such as pipelines and offshore rigs, where traditional methods may not be sufficient. Additionally, advanced monitoring techniques using artificial intelligence (AI), and machine learning (ML), based solutions offer promising advancements, but they introduce new challenges related to cybersecurity, data management, and the need for specialized personnel. This review paper explores the different types of corrosion, detection techniques, their respective limitations, and the potential solutions to address these issues to ensure the long-term sustainability of the oil and gas industry.

Keywords: Corrosion Mechanism, Corrosion Detection Techniques, Corrosion Monitoring, Oil and Gas industry.

1. Introduction

For a couple of decades, the oil and gas industry has proved to be a dominant source of energy acting as a pillar in meeting the global increasing energy demands. The extraction, processing, and sale of oil generate a substantial number of jobs across various fields globally [1]. However, this critical field faces several challenges, among which corrosion is predominant and exists as a substantial threat. This persistent issue cuts across the industry's massive system of pipelines, storage facilities, refineries, reservoirs, and consumer infrastructure [2-4]. Corrosion may lead to leakages of highly combustible oil products exposing the environment to pollution or other catastrophes such as explosions, fatalities, and property loss [5-6]. Conventionally, the industry functions in three separate sections; the upstream, midstream, and downstream. Operations such as exploration and extraction of crude oil are done in the upstream section, transportation, and storage in the midstream while oil refining, marketing, and petroleum products distribution are accomplished in the downstream section [7-8]. In all these sections, a vast network of oil pipes and flowlines exists demanding frequent inspections and substantial resource distribution [9-11]. Moreover, preventive maintenance and inspection of these hazardous pipelines are

particularly challenging, as most are located underground. In addition, external real-time examination of pipelines extending over long distances is nearly unfeasible [12-13]. Although traditional human inspection methods are commonly used, they are often time-consuming and labour-intensive. These methods also have inherent limitations, including inspector fatigue, the potential for errors, and safety risks, particularly in hazardous environments [14-15]. So, using various technologies can detect leaks early, preventing accidents and minimizing damage. This technology enables accurate detection of deteriorating processes and optimizes resource distribution by analytically identifying areas susceptible to corrosion [16-17]. Therefore, using robots equipped with advanced sensor technology is essential for inspecting these pipelines to ensure their safe functionality [18-19]. Sensor technologies have emerged as a critical tool, offering real-time, accurate, and efficient solutions to mitigate corrosion-related challenges [20-21].

This research paper explores various corrosion detection techniques used to identify corrosion at different stages. These techniques include corrosion coupons, electrochemical sensors, ultrasonic testing sensors, pipeline inspection gauges, radiographic testing, magnetic flux leakage sensors, electromagnetic testing, acoustic emission techniques, optical fiber system monitoring, and advanced methods incorporating artificial intelligence and machine learning. Each method has its advantages and limitations depending on factors like the type of corrosion, material, and accessibility of the inspection site. This review emphasizes the critical impact of corrosion in the oil and gas industry and underscores the importance of early detection.

2. Corrosion Mechanism in oil and gas Industry

Corrosion is the gradual and ongoing degradation of metallic materials, typically caused by chemical or electrochemical reactions [22]. This process is accelerated by various factors such as temperature, moisture, pressure, and exposure to chemicals [23]. Figure 1, illustrates the corrosion process. Rusting occurs through two primary reactions: oxidation at the anode, where iron releases electrons to form iron ions, and reduction at the cathode, where oxygen and electrons combine to produce hydroxide ions. These reactions, driven by water and oxygen, work together to promote the formation of rust [24-25].

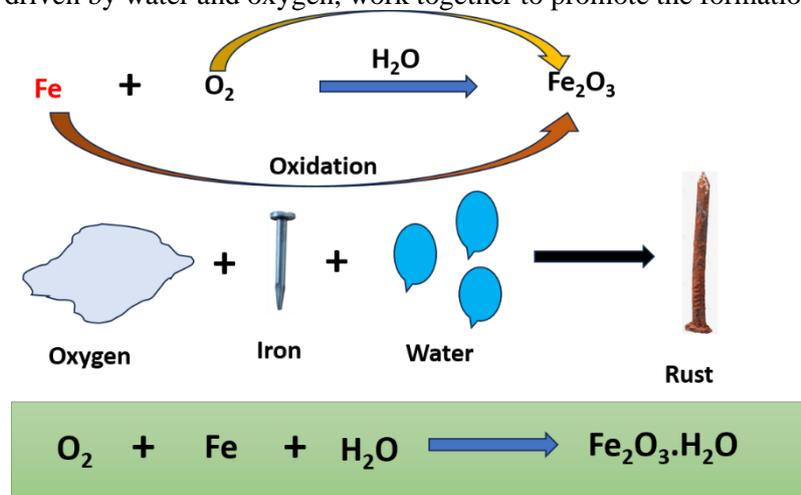


Figure 1 Corrosion Process

3. Types of Corrosion in the Oil & Gas Industries

3.1 Carbon dioxide Corrosion

Carbon dioxide (CO_2) corrosion, also known as "sweet corrosion," is a common type of corrosion in the oil and gas industry [26]. CO_2 corrosion is a well-known issue in the extensive pipeline networks used for oil extraction, transportation, and storage [27]. Although dry CO_2 gas is not corrosive within the temperature ranges typically found in oil production facilities, it becomes corrosive when dissolved in an aqueous phase, where it reacts with steel and the surrounding water [28]. Figure 2 illustrates the process CO_2 corrosion.

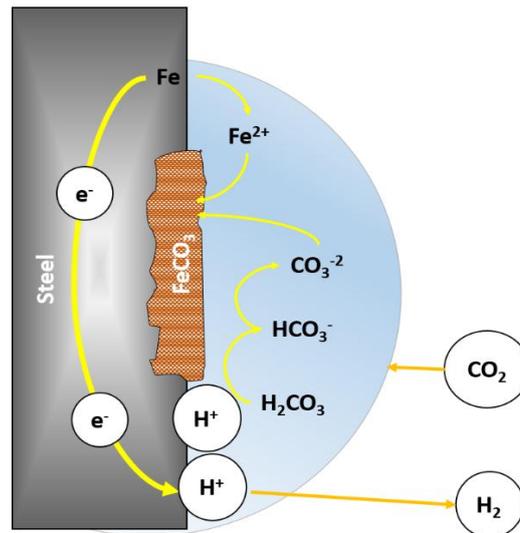


Figure 2 Carbon Dioxide Corrosion

The mechanism of CO₂ corrosion reaction is given by equations (1)-(4). CO₂ corrosion produces carbonic acid as CO₂ combines with H₂O.

a) Carbonic Acid formation: When CO₂ dissolves in water, it reacts to form carbonic acid:



Carbonic acid dissociates further, producing bicarbonate (HCO₃⁻) and Carbonate (CO₃²⁻) ions.



b) Reactions on steel surface: The anodic reaction involves the dissolution of iron (Fe) from the steel surface.



Simultaneously, the cathode reaction occurs, where protons (H⁺) are reduced, primarily from dissociated carbonic acid: 2H. To mitigate CO₂ corrosion, the industry employs several corrosion control strategies such as use of corrosion-resistant materials, corrosion inhibitors, protective coatings and linings, and cathodic protection systems that reduce metal oxidation.

3.2 Hydrogen Sulfide (H₂S) Corrosion

Hydrogen sulfide is a highly aggressive gas that forms a weak acid, hydrogen sulfide acid, upon contact with an aqueous medium [29-30]. This acid contributes to H₂S-induced corrosion, accelerating the degradation of materials, particularly iron and steel. H₂S reacts with iron oxides to form iron sulphides, which precipitate as corrosion product deposits [31-32]. These deposits promote localized forms of corrosion, such as pitting and crevice corrosion, as illustrated in Figure 3.

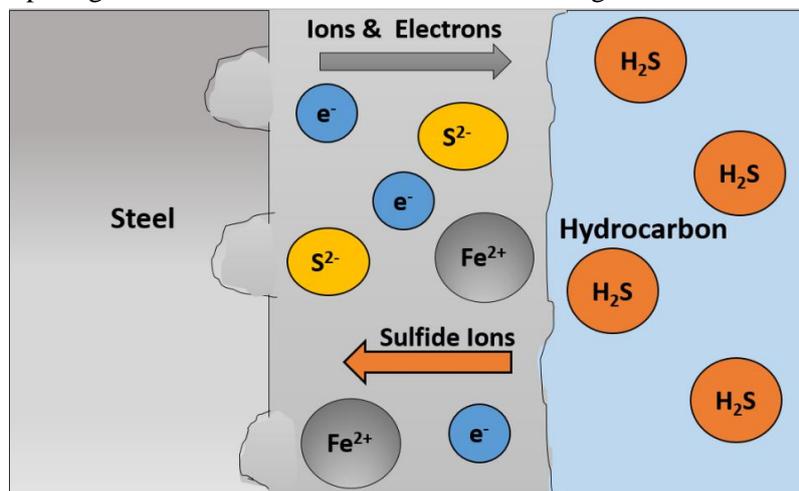


Figure 3 Hydrogen Sulphide Corrosion

The H₂S corrosion mechanism progresses through four distinct stages, as described below:

Stage 1 (Cathodic zone): H₂S dissociates in water (H₂O), producing hydronium ions (H⁺) and bisulfide ions (HS⁻).

Stage 2 (Cathodic zone): The bisulfide ion (HS⁻) further dissociates, generating additional hydronium ions (H⁺) and sulfide ions (S²⁻).

Stage 3 (Anodic zone): Iron (Fe) in the metal oxidizes at the anode, producing ferrous ions (Fe²⁺).

Stage 4: The hydronium ions (H⁺) from stages 1 and 2 react with ferrous ions (Fe²⁺) and are reduced to atomic hydrogen (H), forming iron sulphides (FeS or FeS_x) as corrosion products and releasing molecular hydrogen (H₂). Regular monitoring and inspection techniques, such as electrochemical sensors, ultrasonic testing (UT), and hydrogen probes, are essential for detecting early signs of H₂S corrosion and implementing timely corrective measures.

3.3 Corrosion due to Oxygen

Oxygen (O₂) is a potent oxidizing agent that rapidly accelerates the corrosion of metals, particularly in drilling operations [33-34]. Oxygen can enter drilling fluids through leaking seals, open hatches, and vents. Once present, it significantly increases the corrosion rate, even at low concentrations, by facilitating electrochemical reactions that sustain metal degradation. Additionally, the presence of O₂ intensifies the corrosive effects of H₂S and CO₂, further increasing material deterioration [35-36]. The corrosion mechanism initiated by oxygen is illustrated in Figure 4, where localized anodic and cathodic sites play a critical role. Corrosion begins when a defect or hole in the protective coating exposes the underlying metal to oxygen and water.

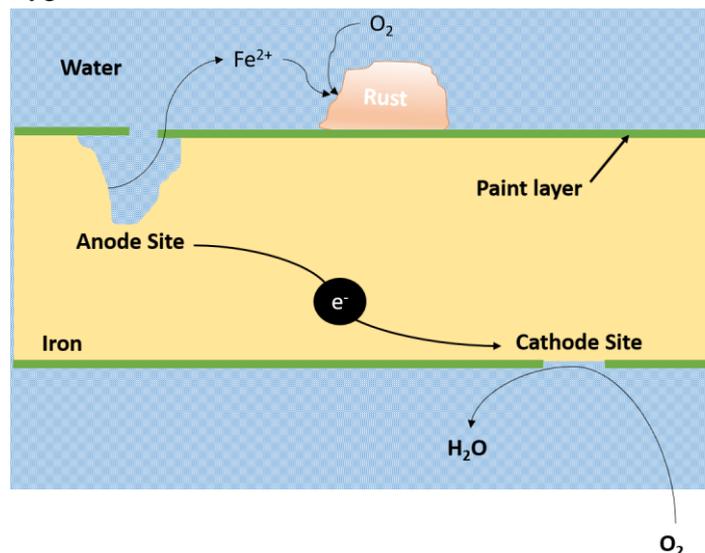


Figure 4 Corrosion due to Oxygen

At the anodic site, iron (Fe) undergoes oxidation



Iron atoms lose electrons producing ferrous ions (Fe²⁺).

At the cathode site, oxygen is reduced in the presence of water:



This reaction consumes the electrons released at the anodic site, creating hydroxide ions (OH⁻)

The Fe²⁺ ions produced at the anodic site diffuse to locations where they react with oxygen, often remote from the anodic site. This reaction forms insoluble hydrated iron oxides (Fe³⁺), commonly known as rust.



Overtime, Fe(OH)₃ dehydrates to form rust (Fe₂O₃ .xH₂O). Oxygen reduction at the cathodic site sustains the electrochemical reactions, while iron oxidation at the anodic site causes localized material loss. These interactions between anodic and cathodic sites lead to the formation of pits beneath the protective coating (Figure 4). These pits can grow significantly, ultimately causing structural failure with little visible warning.

3.4 Corrosion due to Galvanic Action

When metals with different electrochemical potentials come into contact in a conducive environment, galvanic corrosion is likely to occur [37-38]. The metal more susceptible to corrosion acts as the anode and begins to corrode, releasing metal ions to maintain electron balance. Due to the crystalline structure of metals, numerous microscopic galvanic cells form, resulting in corrosion between the granular layers [39-40].

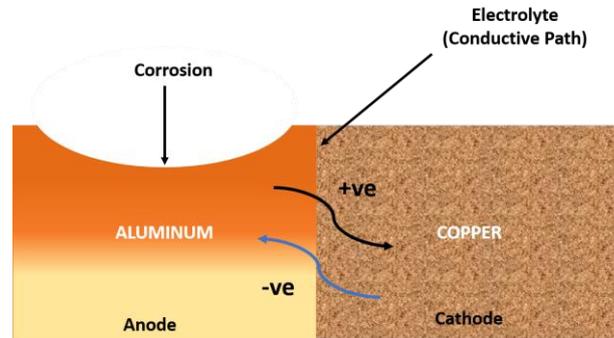


Figure 5 Galvanic corrosion in dissimilar metal

Figure 5, illustrates this phenomenon, highlighting galvanic corrosion between dissimilar metals, with aluminum acting as the anode and copper as the cathode. Aluminum, being less noble, serves as the anode where corrosion initiates, while copper, being more noble, functions as the cathode and remains protected.

At the anode, aluminium undergoes oxidation, releasing metal ions into the electrolyte:



This process results in the degradation of aluminum, as indicated by the label "corrosion" in Figure 5. At the cathode, the electrons released during the oxidation of aluminum travel through the metallic connection to copper. These electrons participate in a reduction reaction at the copper surface, often involving oxygen from the environment:



The cathode remains unaffected by this reaction, as shown in the diagram.

3.5 Crevice corrosion

Crevice corrosion typically occurs in the small spaces between thin metal clearances, or crevices, where fluid becomes stagnant. This results from variations in the concentration of corrodents on a metal surface [41-42]. Pitting or crevice corrosion (fig. 6), which entails selective degradation, occurs because of disparities in electrochemical potential. Occurrence of dissolved oxygen in drilling fluid accelerates the loss of metal and pitting in shielded sections of the drill string, often leading to failures, and damage beneath the shields of the rubber pipe [43].

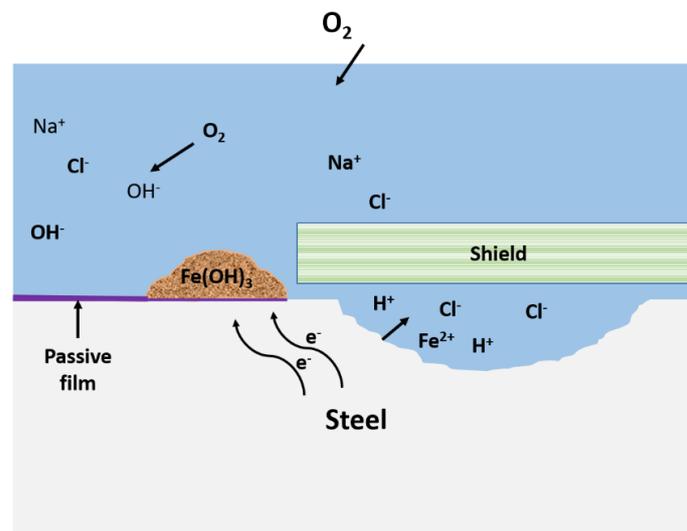


Figure 6 Crevice corrosion

3.6 Corrosion due to erosion

Erosion corrosion occurs when a material's surface undergoes accelerated wear due to the combined effects of mechanical abrasion and electrochemical corrosion [44-45]. Figure 7 shows the process of corrosion due to erosion and its effect.

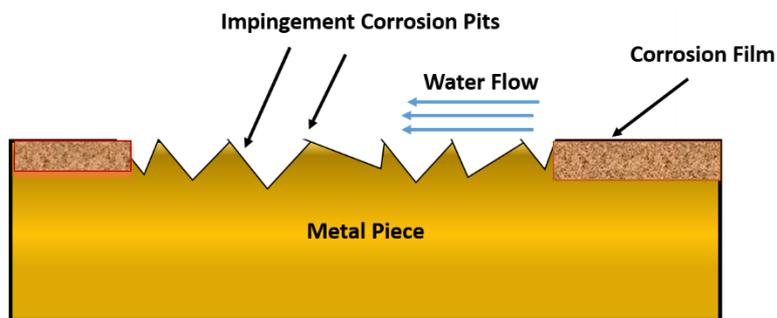


Figure 7 Corrosion due to erosion

This process is particularly prominent in environments where high-velocity fluids or suspended solid particles continuously impact the material surface. The rapid flow removes protective corrosion products or coatings, exposing fresh metal to the corrosive medium. Over time, this repeated exposure results in significant material degradation, often characterized by grooves, pits, or a washed-out appearance. Erosion corrosion is commonly observed in pipelines, pump impellers, and heat exchangers, where turbulent flow conditions are prevalent [46].

3.7 Microbiologically induced corrosion

Microbiologically Induced Corrosion (MIC) is a specialized form of corrosion caused by microbial activity, often involving sulphate-reducing bacteria (SRB), acid-producing bacteria, or other microorganisms [47-48]. Bacterial action is the primary driver of this type of corrosion, as microbes produce harmful byproducts such as carbon dioxide, hydrogen sulfide, and acidic substances that make the fluid in pipelines more toxic. These byproducts not only degrade the metal surface but also facilitate accelerated corrosion. Microbes typically establish colonies in favourable environments, such as stagnant or low-flow areas, where they promote faster corrosion underneath the biofilm or deposit layers. As shown in Figure 8, one of the primary mechanisms involves sulphate-reducing bacteria reducing sulphate (SO_4^{2-}) to form sulfides, which then react with iron to create iron sulfide (FeS). Chloride ions (Cl^-) further contribute by penetrating the protective passive oxide layer on metals like stainless steel, exposing the surface to attack. Microbial activity produces acids and reactive byproducts, such as hydrogen ions (H^+), which degrade the passive layer, leaving the metal susceptible to further corrosion. At anodic sites, iron dissolves into the electrolyte, forming ferrous (Fe^{2+}) or ferric (Fe^{3+}) ions. Additionally, microbial metabolism results in degradation products like sulfite (SO_3^{2-}), exacerbating the corrosion process. Acid-producing bacteria further accelerate corrosion by generating organic acids that lower the pH, creating an even more aggressive environment. Together, these processes demonstrate how microbial action transforms a localized environment into a highly corrosive one, posing significant challenges to industrial and marine pipelines and systems [49-50].

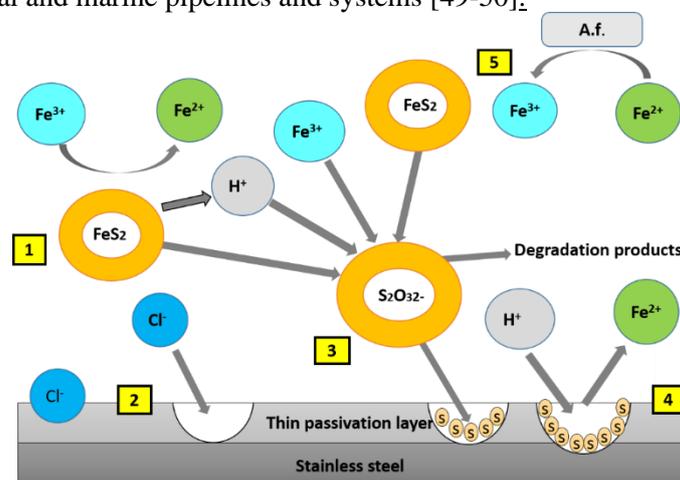


Figure 8 Microbiologically induced corrosion

4. Corrosion detection techniques

Several techniques have been employed to detect corrosion in the oil and gas industry to proactively monitor asset health, optimize maintenance strategies, and improve overall operational efficiency while ensuring compliance with industry safety and environmental regulations.

4.1 Corrosion Coupon

The corrosion coupon weight loss measurement is one of the most reliable and long-established methods for determining corrosion rates in the industry [51-52]. Despite the development of various corrosion monitoring techniques, weight loss measurement remains the most widely used method for assessing corrosion rates. The basic procedure involves installing a corrosion coupon made of the material of interest, with a predetermined weight and shape, in a corrosive environment for a set period. After exposure, the coupon is removed, weighed, and examined for erosion. Due to its simplicity, versatility for different materials and shapes, and basic principle, the corrosion coupon method is widely utilized. However, installing, removing, and analysing the coupons after corrosion is time-consuming. They only provide average corrosion rates over a specific period and do not offer real-time data for oil field facilities [53].

4.2 Electrochemical Sensors

Electrochemical sensors play a crucial role in detecting and monitoring corrosion in these environments by utilizing advanced techniques such as electrochemical impedance spectroscopy (EIS), galvanic current evaluation, electrochemical noise (EN), and linear polarization resistance (LPR) [54-55]. These sensors provide real-time measurements of corrosion rates and help in understanding the mechanisms of material degradation caused by exposure to aggressive substances like H_2S , CO_2 , and Chloride ions (Cl^-), which are commonly present in oil and gas operations [56]. Among these techniques, the LPR method is widely used due to its ease of operation and data interpretation, making it a preferred choice for commercial applications. Unlike traditional three-electrode systems, most industrial LPR probes use electrodes made from the same material as the monitored pipeline or structure, ensuring accurate results. In the oil and gas sector, electrochemical sensors are employed to monitor corrosion in both subsurface (downhole) and surface equipment. Figure 9, illustrates the Electrochemical sensor for monitoring corrosion condition.

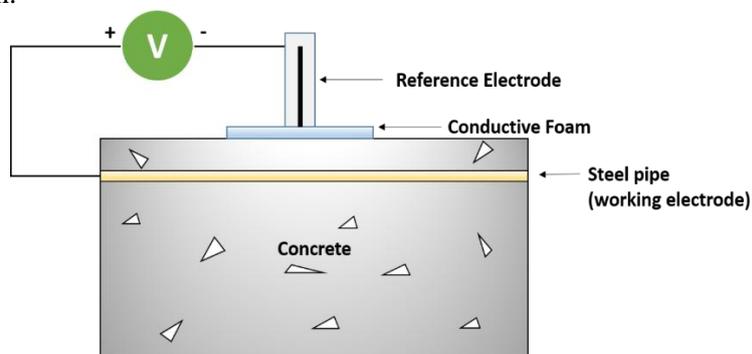


Figure 9 Electrochemical sensor

The typical sensor setup consists of a reference electrode, a working electrode (pipeline steel or alloy material), conductive foam, and a voltmeter. The reference electrode provides a stable baseline for potential measurement, while the working electrode undergoes electrochemical reactions due to exposure to corrosive agents like brine, sour gas (H_2S), CO_2 , and microbial biofilms. The conductive foam ensures proper electrical contact with the pipeline surface, enabling uniform current distribution. In this system, the electrochemical half-cell potential method is commonly employed, where a highly negative potential (typically below -350 mV versus a reference electrode, such as $Cu/CuSO_4$) indicates an elevated risk of corrosion [57-58]. This monitoring approach is particularly valuable in offshore rigs, subsea pipelines, and high-pressure gas wells, where corrosion can lead to catastrophic failures if left undetected.

Despite their effectiveness, electrochemical sensors have some limitations. One major drawback is that an externally applied current can sometimes accelerate corrosion, leading to overestimated corrosion rates. To prevent this, careful selection of the electrode system design and optimization of electrochemical variables such as applied voltage, scanning speed, and corrosion rates are crucial.

Another limitation is that these sensors are not inherently suitable for non-conductive environments, as they typically require an ion-conductive electrolytic medium like an aqueous solution. However, with proper packaging and advanced materials, electrochemical sensors can withstand extreme conditions in oil and gas operations, functioning at temperatures exceeding 300°C and pressures up to 34.5 MPa (5000 psi) [59-60].

This method provides crucial data that help oil and gas companies implement preventive measures such as protective coatings, corrosion inhibitors, cathodic protection, and material selection improvements. Their ability to operate in harsh environments makes them invaluable tools for enhancing asset integrity, reducing maintenance costs, and preventing environmental hazards caused by pipeline failures or equipment degradation.

4.3 Ultrasonic Testing Sensor

Ultrasonic Testing (UT) is a widely used non-destructive testing (NDT) technique for assessing the structural integrity of pipelines, storage tanks, and other critical infrastructure in oil and gas industry. UT plays a vital role in detecting corrosion, cracks, and material degradation, helping prevent failures that could lead to operational disruptions, environmental hazards, and safety risks [61-62]. Figure 10, illustrates the setup of ultrasonic sensors for evaluating the structural health of pipes and their operating principle in detecting flaws or corrosion.

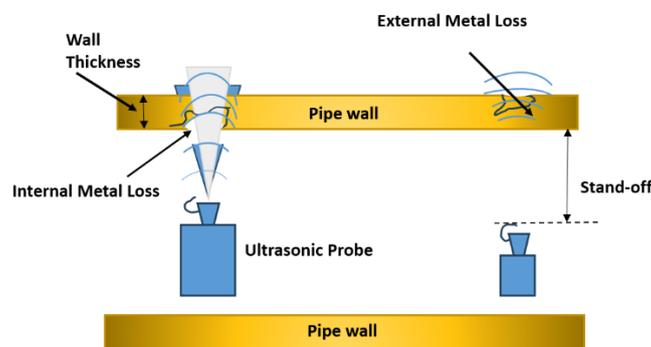


Figure 10 Ultrasonic testing sensor

Ultrasonic corrosion detection relies on a piezoelectric transducer to generate high-frequency sound waves typically in the MHz range, which are directed at the pipe wall at a right angle [63]. When these ultrasonic waves encounter different surfaces, including external and internal surfaces, material discontinuities, or corroded areas, they reflect back to the transducer. The system then calculates wall thickness by analysing the time delay between the echoes returning from the inner and outer surfaces of the pipe [64-65]. A reduction in wall thickness indicates corrosion, while irregular reflections may suggest pitting or structural flaws. Ultrasonic sensors in the oil and gas sector come in two main types a) portable ultrasonic thickness gauges for periodic inspections b) permanently mounted ultrasonic sensors for continuous monitoring, particularly in high-risk areas such as offshore platforms, subsea pipelines, and refining units [66-67]. Additionally, ultrasonic sensors can be integrated into Pipe Inspection Gauges (PIGs) autonomous devices that travel inside pipelines to perform internal inspections, detecting corrosion, erosion, and mechanical defects. While ultrasonic testing is highly effective, it has certain limitations. Higher ultrasonic frequencies offer greater resolution; however, detecting shallow corrosion or thin material loss can still be challenging. Furthermore, ultrasonic waves may be less effective when thick deposits of mud, scale, or wax are present on pipe walls, as these materials can absorb or scatter the sound waves. Despite these challenges, UT remains a crucial tool in oil and gas corrosion management, ensuring asset longevity, reducing maintenance costs, and preventing catastrophic failures [68].

4.4 Pipeline Inspection Gauge

The Pipeline Inspection Gauge (PIG) system is a crucial tool used in the oil and gas industry to inspect the internal condition of pipelines [69]. Pipeline inspection devices, commonly referred to as PIGs, are equipped with a variety of sensors and tools for pipe cleaning as shown in Figure 11. As it moves, it inspects the pipeline's interior for damage, corrosion, or irregularities using sensors, cameras, and diagnostic tools. The PIG's position is tracked by an odometer and transmitter, with signals detected by dual tracking receivers on the surface [70]. The collected data is sent to a control centre for analysis, helping detect potential issues like weak spots or blockages. Once the inspection is complete, the PIG

exits the pipeline, and any identified problems are addressed to ensure safe pipeline operation. Regulatory standards or company protocols often require PIGs to be run for inspections every 5 to 7 years [71-72]. However, the cost of In-line Inspection gadgets limits their frequency of use. While PIGs provide thorough inspections, they do not offer continuous monitoring, highlighting the need for affordable sensors that can provide ongoing corrosion tracking in the oil and gas industry.

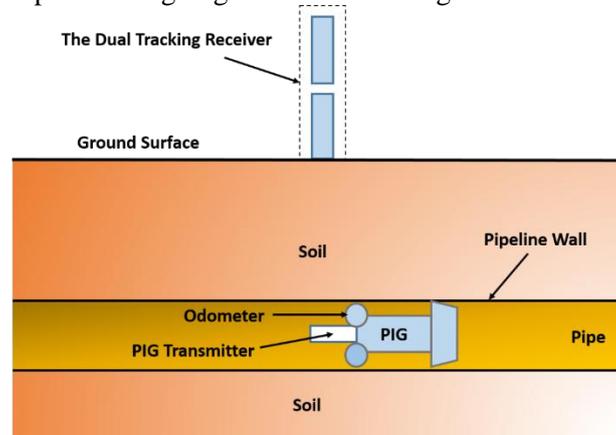


Figure 11 Pipeline Inspection Gauge

4.5 Radiography Tests

Radiographic Testing (RT) is a widely used NDT method for detecting both internal and external corrosion, pitting, and wall thickness reductions that may compromise the structural integrity of oil and gas infrastructure [73-74].

This technique employs either x-rays or gamma rays to penetrate materials and create an image that reveals internal irregularities caused by corrosion as shown in Figure 12. Techniques like X-rays and gamma rays can detect subsurface flaws within material and radiographs of these anomalies can be obtained [75]. If corrosion has thinned the material, these images can be shown. Regular inspection methods for hidden damage usually require removing insulation, which can be a hassle. However, new high-frequency techniques like microwave radiography can detect hidden corrosion without needing to take off the insulation. Corrosion detection under insulation can be improved by integrating microwave technology with machine learning (ML) [76-77]. This approach goes beyond traditional methods, exploring how ML can solve new possibilities and overcome limitations with microwave techniques. Microwave inspections aren't perfect. One of the key advantages of RT in corrosion detection is its ability to inspect complex geometries and in-service pipelines without requiring shutdowns [78]. Additionally, digital radiography techniques enable faster image processing and remote analysis, improving efficiency. However, RT does come with challenges, including radiation safety concerns, higher costs compared to other NDT methods like Ultrasonic Testing (UT), and limitations when inspecting very thick-walled components [79]. Despite these challenges, RT remains a crucial technology in ensuring the safety and longevity of oil and gas infrastructure.

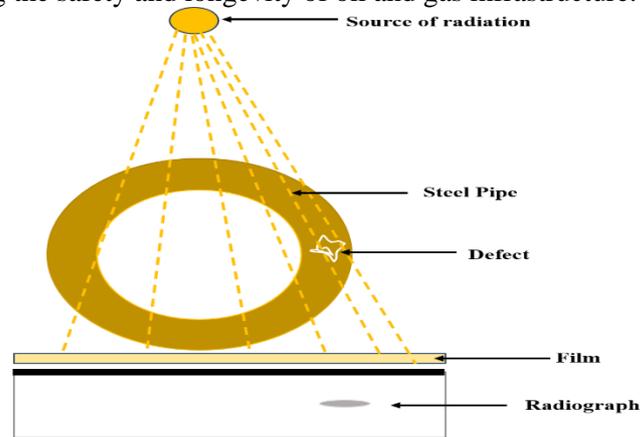


Figure 12 Radiography Tests

4.6 Magnetic Flux Leakage (MFL) Sensor

The magnetic flux leakage (MFL) sensor is a widely used NDT method for detecting corrosion and metal loss in steel pipelines, particularly in the oil and gas industry for a long time [80-81]. It can identify the position, alignment, and even anomalies that are situated within or outside the pipe. Figure 13, below represents the magnetic flux leakage sensor and its working.

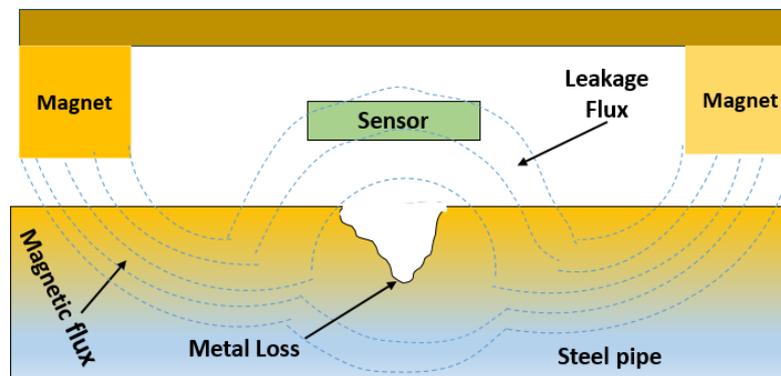


Figure 13 Magnetic Flux Leakage Sensor

MFL sensors use a magnet on one side and an inductor coil that acts as a sensor on the other side of the inspected material. Further, a magnetic field created by a permanent magnet travels through the material to detect any flaws or irregularities such as corrosion (metal loss), cracks or porosities, that interfere with the magnetic field lines, resulting in magnetic flux leakage. Further, the sensor coil detects this magnetic flux leakage, enabling the identification and localization of anomalies within the material [82]. Traditional MFL systems generate magnetic field lines aligned with the pipe's axis during inspection and hence are less efficient in detecting anomalies that are elongated and aligned parallel to the magnetic field. To address this, Hui Min Kim et al. [83] introduced a novel approach known as Transverse Field Inspection (TFI), which differs from conventional MFL structures. This method optimizes circumferential magnetic fields to enhance the detection of elongated cracks resulting from variations in external and internal pressure. T.D. Williamson Inc. et al [84] has developed Spiral Magnetic Flux Leakage (SMFL), combining the capabilities of traditional MFL and circumferential MFL (CMFL), allowing the detection of both perpendicular anomalies and long, thin cracks. Quang Pham et al. [85], have developed advanced magnetic sensors, including a planar Hall magneto-resistance sensor, to enhance MFL applications. Their findings demonstrated improvements in both the bipolar and linear responses to magnetic fields, along with heightened sensitivity and reduced thermal drift. Finite Element Analysis (FEA) technique is also frequently used to ascertain the parameters that influence the MFL signal. Liang Chen et al. [86] investigated MFL signals relating to four distinct corrosion anomalies using three-dimensional FEA, concluding the placement of corrosion relative to the pipeline that influence peak-to-peak value of the MFL signal. Okolo et al. [87] introduced a quantitative strategy using Pulsed Magnetic Flux Leakage (PMFL) to analyze hairline cracks, demonstrating that this method effectively categorizes these defects. A critical factor influencing the efficacy of MFL is the processing of inspection signals. Mao et al. [88] conducted an extensive study on MFL signal processing. In a 2006 study, Carvalho et al. [89] used neural networks to differentiate signals gathered longitudinally on welds, classifying them into defective and non-defective categories. Their research demonstrated an accuracy of 94% for the initial classification and 71% for subsequent classification. Similarly, Ma et al. [90] successfully analyzed MFL signals using an immune radial basis function artificial neural network (ANN), accurately pinpointing the location and extent of corrosion damage. Mohamed Layouni et al. [91] employed pattern-adapted wavelets to assess the length of anomalies and ANNs to determine their depth. Their method demonstrated computational efficiency, high precision, and applicability to various anomaly forms.

When processing MFL signals, noise removal is essential for accurate detection. Fengzhu Ji et al. [92] introduced an algorithm called the adaptive fuzzy lifting wavelet transform to improve noise reduction in MFL signals. Their results indicated superior noise reduction compared to traditional wavelet transforms. Mukherjee et al. [93] proposed a channel equalization algorithm designed to rectify misalignments in MFL devices, leading to exceptional signal recovery and noise elimination. As AI and

ML continue to advance, they are being integrated into MFL systems to improve defect classification and minimize false positives. Despite challenges in detecting certain anomaly types, MFL remains a crucial tool for ensuring pipeline integrity, preventing failures, and maintaining the safety and efficiency of oil and gas infrastructure.

4.7 Electromagnetic testing (ET)

Electromagnetic testing (ET) is a non-destructive testing method that uses the principle of electromagnetic induction for the detection of flaws in surface and subsurface levels [94] as shown in Figure 14.

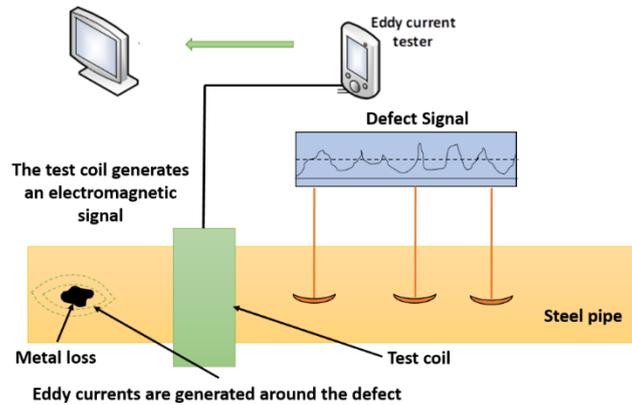


Figure 14 Shows working principle of Electromagnetic Testing

When an electric current is made to flow through the test coil, a magnetic field is generated around it. When this coil is placed near an electrically conductive material such as metallic oil pipe or tank, eddy current will be induced in that material if the pipe or tank has corroded parts or cracks, these flaws will interrupt the eddy current circulation and the magnetic coupling with the probe will be changed and thus a defect signal can be read at the eddy current tester after measuring coil impedance variations [95]. This is especially important for a hidden type of corrosion called Corrosion Under Coating (CUC), which can damage the metal beneath a non-conductive layer. This corrosion is a danger because it significantly reduces the structural integrity. Further, Karsten Husby et al., [96] generated training data for ML that mirrors real-world scenarios by aligning the calibration of both the Vector Network Analyzer (VNA) and the Eddy Current Testing (ECT) tool, and utilizing a standard 1-port calibration within the magnetic field. The AI algorithm, developed through this approach, demonstrates remarkable precision in assessing the thickness of duplex coatings, which plays a pivotal role in protecting carbon steel bases from corrosion. In addition, this technique can be applied in performing tasks such as weld examination, identifying cracks, and even gauging wall thickness.

4.8 Acoustic Emission (AE) Technique

The AE technique is a powerful NDT method for detecting corrosion and structural damage in the oil and gas industry. The AE method involves the detection of ultrasonic signals naturally produced by materials under stress, typically indicating irreversible occurrences such as corrosion [97-98]. The analysis of ultrasonic pulses released during the formation of cracks allows for the early identification of potential mechanical damage by detecting pioneer signals of cracks.

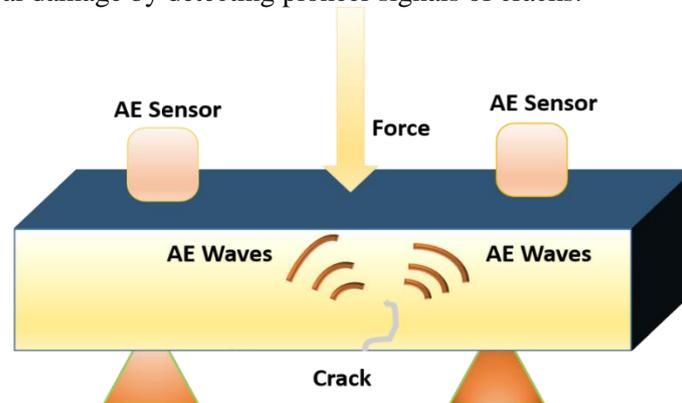


Figure 15 AE Sensor

As shown in Figure 15, when a crack forms or propagates due to applied force, AE waves are emitted from the defect location and travel through the material. AE sensors capture these waves and convert them into electrical signals, which can be analyzed to determine the presence, location, and severity of corrosion related defects [99]. In the oil and gas industry, pipelines and storage tanks are exposed to harsh environmental conditions, leading to corrosion and structural weakening. The AE technique detects real-time signals generated by active corrosion processes or crack propagation within the metal. Compared to traditional inspection methods, AE testing is highly sensitive to detect microscopic crack formation and material degradation in real time. Additionally, AE testing is effective for inspecting large structures without requiring direct access to the defect location, making it suitable for monitoring buried or insulated pipelines [100]. By using multiple AE sensors, engineers can triangulate the source of the emission signals, enabling precise localization of corrosion damage or crack initiation. Further, the AE technology have integrated with ML techniques to enhance corrosion detection and analysis. Ciaburro et al. [101] investigated various AE systems used for monitoring and examining materials and structures. Their study explores how ML can detect, locate, and characterize fractures while predicting failure. The widespread application of these techniques highlights their efficacy in detecting structural damage even in environments with high levels of noise interference. Even a new classification method for AE signals related to corrosion was introduced, where synthetic data were initially used to validate this approach. Additionally, a study by Muhammad Fahad Sheikh et al. [102] showed that sound well AE sensors could effectively detect AE signals during accelerated corrosion tests. Their research proposes a novel method that combines AE signals with ML to predict corrosion severity with high accuracy. This approach significantly improves the ability to assess and predict corrosion damage, making it a valuable tool for proactive maintenance in the oil and gas industry.

4.9 Optical Fiber System Monitoring Technique

Optical Fiber Sensing (OFS) has developed as a promising system for monitoring carbon steel corrosion [103]. This method exploits the interaction between light and sound waves within the fiber. As light propagates through the fiber, its electric field induces acoustic waves via a process called electrostriction [104]. OFS, particularly Fiber Bragg Grating (FBG) sensors play a crucial role in corrosion monitoring within the oil and gas industry. As shown in Figure 16 multiple FBG sensors along with an optical fiber, are attached to the outer surface of a pipeline. Each FBG sensor acts as a wavelength-selective mirror, reflecting a specific wavelength of light while transmitting the rest. When corrosion occurs, the thinning of the pipeline wall leads to mechanical deformations, which in turn strain the FBG sensors and cause shifts in the reflected wavelength. By continuously monitoring these shifts, the system can detect structural integrity changes in real-time[105-106]. A broadband light source transmits signals through the optical fiber, and a spectrometer analyzes the reflected wavelengths to identify any shifts indicative of corrosion.

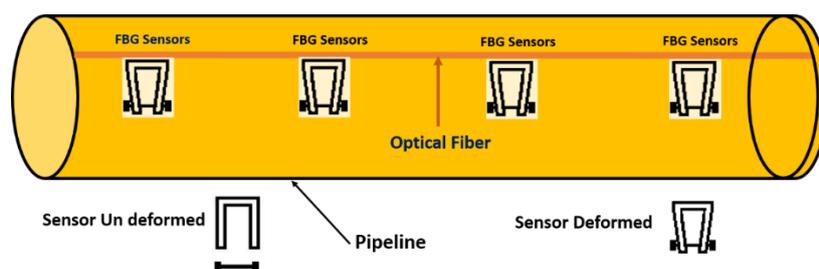


Figure 16 Optical fiber sensor

4.10 Artificial Intelligence and Machine Learning Technique

AI and ML are playing a crucial role in corrosion detection and monitoring in the oil and gas industry. These technologies provide advanced solutions for identifying, predicting, and mitigating corrosion-related issues, enhancing maintenance efficiency, and reducing operational risks [107-108]. One of the primary applications of AI and ML in this domain is automated corrosion mapping, where AI algorithms analyse facility imagery to detect and classify atmospheric corrosion, offering a comprehensive view of equipment health and aiding in maintenance planning. Additionally, ML models are used for predictive modelling, analysing vast datasets that include environmental factors and material properties to forecast corrosion levels, enabling proactive maintenance strategies [109-110]. Deep learning techniques, such as convolutional neural networks, further enhance the accuracy of corrosion detection by automatically segmenting affected areas in infrastructure images, reducing the need for manual inspections [111-112].

Moreover, AI-driven predictive maintenance systems continuously monitor equipment conditions in real-time, predicting potential failures due to corrosion and allowing timely interventions to minimize downtime and maintenance costs. The use of AI and ML technologies enhances safety, operational efficiency, and cost-effectiveness in the oil and gas sector by enabling early detection and efficient management of corrosion-related risks.

5. Challenges and future scope in Oil and Gas Industry

Corrosion is a major challenge in the oil and gas industry, affecting structural integrity and increasing life cycle costs. Carbon steel, widely used for pipework, is highly susceptible to corrosion under extreme operational conditions. The hostile downhole environment, with high pressure, temperature variations, and corrosive elements like CO₂, H₂S, and chlorides, complicates real-time corrosion monitoring and accelerates material degradation. Additionally, the vast pipeline networks spanning thousands of kilometres make real-time corrosion detection difficult due to inaccessibility and unpredictable corrosion sites. Traditional inspection methods are often inadequate, particularly for internal monitoring, while deep gas wells further complicate data acquisition, requiring reliable wireless communication solutions. Corrosion mechanisms such as “sweet corrosion” (from CO₂) and “sour corrosion” (from H₂S) contribute to material degradation and increase susceptibility to SSC. Real-time data acquisition remains challenging due to limitations in sensor technology, including cement alkalinity and electromagnetic interference. Maintaining and inspecting pipelines, particularly underground and long-distance sections, requires substantial resources, making advanced sensor-based monitoring and robotic inspection essential. Addressing these challenges requires continuous advancements in corrosion monitoring, material science, and inspection technologies to enhance safety, reduce operational costs, and ensure the longevity of oil and gas infrastructure. The integration of AI, ML, and IoT-based monitoring systems requires significant investment and skilled personnel for implementation and maintenance. Additionally, real-time data collection and analysis introduce cybersecurity risks, making secure data management a critical concern. Another challenge is the development of cost-effective and environmentally friendly corrosion inhibitors that comply with regulatory standards without compromising performance. Addressing these issues is crucial for enhancing corrosion detection, reducing operational risks, and ensuring the long-term sustainability of the oil and gas industry.

6. Conclusion

Corrosion remains a critical challenge in the oil and gas industry, affecting the integrity, safety, and efficiency of infrastructure. Various types of corrosion, including uniform, pitting, crevice, galvanic, and microbiologically influenced corrosion, pose significant risks to pipelines, storage tanks, and other assets. Effective detection methods are essential for mitigating these risks, ensuring operational reliability, and preventing costly failures. Traditional NDT such as ultrasonic testing, magnetic flux leakage, and radiographic inspection continue to play a crucial role in corrosion assessment. However, recent advancements in artificial intelligence (AI), machine learning (ML), and Internet of Things (IoT)-enabled monitoring systems are revolutionizing corrosion detection by enabling real-time data analysis and predictive maintenance. While these innovations offer promising solutions, challenges such as harsh environmental conditions, high implementation costs, and cybersecurity risks must be addressed. Future research should focus on enhancing detection accuracy, developing cost-effective solutions, and improving the sustainability of corrosion prevention methods. By leveraging cutting-edge technologies and proactive monitoring strategies, the industry can significantly improve asset longevity, operational safety, and cost efficiency.

References

1. Cid-Galiot, J.J., Aguilar-Lasserre, A.A., Rodriguez-Jarquín, J.P., Villanueva-Vasquez, D., Posada-Gómez, R. and Juárez-Martínez, U., 2021. Fault-tolerance techniques and global positioning systems based on artificial intelligence for the analysis of corrosion impact on the pipelines of oil and gas industry. *Journal of Pressure Vessel Technology*, 143(2), p.020801.
2. Khalaf, A.H., Xiao, Y., Xu, N., Wu, B., Li, H., Lin, B., Nie, Z. and Tang, J., 2024. Emerging AI technologies for corrosion monitoring in oil and gas industry: A comprehensive review. *Engineering Failure Analysis*, 155, p.107735.

3. Aljarah, A., Vahdati, N. and Butt, H., 2021. Magnetic internal corrosion detection sensor for exposed oil storage tanks. *Sensors*, 21(7), p.2457.
4. Unueroh, U., Omonria, G., Efosa, O. and Awotunde, M., 2016. Pipeline corrosion control in oil and gas industry: a case study of NNPC/PPMC system 2A pipeline. *Nigerian Journal of Technology*, 35(2), pp.317-320.
5. Vahdati, N., Shirayayev, O., Balachandran, B., Yu, M. and Chopra, N., 2018, May. External and internal corrosion detection sensors for oil and gas pipelines using fiber optics. In *Research and Development Petroleum Conference and Exhibition 2018* (Vol. 2018, No. 1, pp. 60-63). European Association of Geoscientists & Engineers.
6. Popoola, L.T., Grema, A.S., Latinwo, G.K., Gutti, B. and Balogun, A.S., 2013. Corrosion problems during oil and gas production and its mitigation. *International Journal of Industrial Chemistry*, 4, pp.1-15.
7. Al-Janabi, Y.T., 2020. An overview of corrosion in oil and gas industry: upstream, midstream, and downstream sectors. *Corrosion inhibitors in the oil and gas industry*, pp.1-39.
8. Aalsalem, M.Y., Khan, W.Z., Gharibi, W., Khan, M.K. and Arshad, Q., 2018. Wireless Sensor Networks in oil and gas industry: Recent advances, taxonomy, requirements, and open challenges. *Journal of network and computer applications*, 113, pp.87-97.
9. Aalsalem, M.Y., Khan, W.Z., Gharibi, W., Khan, M.K. and Arshad, Q., 2018. Wireless Sensor Networks in oil and gas industry: Recent advances, taxonomy, requirements, and open challenges. *Journal of network and computer applications*, 113, pp.87-97.
10. Razvarz, S., Jafari, R. and Gegov, A., 2021. Flow modelling and control in pipeline systems. *Stud. Syst. Decis. Control*, 321, pp.25-57.
11. Gómez, C. and Green, D.R., 2017. Small unmanned airborne systems to support oil and gas pipeline monitoring and mapping. *Arabian Journal of Geosciences*, 10, pp.1-17.
12. Ma, Q., Tian, G., Zeng, Y., Li, R., Song, H., Wang, Z., Gao, B. and Zeng, K., 2021. Pipeline in-line inspection method, instrumentation and data management. *Sensors*, 21(11), p.3862.
13. Adegboye, M.A., Fung, W.K. and Karnik, A., 2019. Recent advances in pipeline monitoring and oil leakage detection technologies: Principles and approaches. *Sensors*, 19(11), p.2548.
14. Musarat, M.A., Khan, A.M., Alaloul, W.S., Blas, N. and Ayub, S., 2024. Automated monitoring innovations for efficient and safe construction practices. *Results in Engineering*, 22, p.102057.
15. Shindikar, S., 2024. A Systematic Approach for Selection of Autonomous Inspection Technologies in Oilseed Industry.
16. Vahdati, N., Shirayayev, O., Parapurath, S.M., Yap, F.F. and Butt, H., 2022. Cost-Effective Corrosion Detection Sensor for Above-Ground Oil and Gas Flowlines. *Sensors*, 22(21), p.8489.
17. Ray, J.D., Randall, B.V. and Parker, J.C., 1979. Use of reactive iron oxide to remove H₂S from drilling fluid. *Journal of Petroleum Technology*, 31(06), pp.797-801.
18. Sampath, S., Bhattacharya, B., Aryan, P. and Sohn, H., 2019. A real-time, non-contact method for in-line inspection of oil and gas pipelines using optical sensor array. *Sensors*, 19(16), p.3615.
19. Reddy, M.S.B., Ponnamma, D., Sadasivuni, K.K., Aich, S., Kailasa, S., Parangusan, H., Ibrahim, M., Eldeib, S., Shehata, O. and Ismail, M., 2021. Sensors in advancing the capabilities of corrosion detection: A review., 2021, 332. DOI: <https://doi.org/10.1016/j.sna.2021.113086>.
20. Reddy, M.S.B., Ponnamma, D., Sadasivuni, K.K., Aich, S., Kailasa, S., Parangusan, H., Ibrahim, M., Eldeib, S., Shehata, O., Ismail, M. and Zarandah, R., 2021. Sensors in advancing the capabilities of corrosion detection: A review. *Sensors and Actuators A: Physical*, 332, p.113086.
21. Aljibori, H., Al-Amiery, A. and Isahak, W.N.R., 2024. Advancements in corrosion prevention techniques. *Journal of Bio-and Tribo-Corrosion*, 10(4), p.78.
22. Perez, N., 2024. Electrochemical corrosion. In *Materials Science: Theory and Engineering* (pp. 835-898). Cham: Springer Nature Switzerland.
23. Ibrahim, B.E., Nardeli, J.V. and Guo, L., 2021. An overview of corrosion. *Sustainable corrosion inhibitors I: fundamentals, methodologies, and industrial applications*, pp.1-19.
24. Perez, N., 2024. Electrochemical corrosion. In *Materials Science: Theory and Engineering* (pp. 835-898). Cham: Springer Nature Switzerland.
25. Furlan, P.Y., Jaravata, E.J., Furlan, A.Y. and Kahl, P., 2023. Will it rust? A set of simple demonstrations illustrating iron corrosion prevention strategies at sea. *Journal of Chemical Education*, 100(2), pp.1081-1088.
26. Mohamed, A. and Oyekola, P., 2020. Carbon dioxide corrosion in oil and gas industry. *Carbon*, 29(7), pp.10053-10065.
27. Eduok, U. and Szpunar, J., 2020. Corrosion inhibitors for sweet oilfield environment (CO₂ corrosion). *Corrosion Inhibitors in the Oil and Gas Industry*, pp.177-227.
28. Brondel, D., Edwards, R., Hayman, A., Hill, D., Mehta, S. and Semerad, T., 1994. Corrosion in the oil industry. *Oilfield Review*;(Netherlands), 6(2).
29. Chan, Y.H., Lock, S.S.M., Wong, M.K., Yiin, C.L., Loy, A.C.M., Cheah, K.W., Chai, S.Y.W., Li, C., How, B.S., Chin, B.L.F. and Chan, Z.P., 2022. A state-of-the-art review on capture and separation of hazardous hydrogen sulfide (H₂S): Recent advances, challenges and outlook. *Environmental Pollution*, 314, p.120219.
30. Wen, X., Bai, P., Luo, B., Zheng, S. and Chen, C., 2018. Review of recent progress in the study of corrosion products of steels in a hydrogen sulphide environment. *Corrosion Science*, 139, pp.124-140.
31. Ning, J., Zheng, Y., Brown, B., Young, D. and Nešić, S., 2017. The role of iron sulfide polymorphism in localized H₂S corrosion of mild steel. *Corrosion*, 73(2), pp.155-168.

32. Hamza, A., Hussein, I.A., Jalab, R., Saad, M. and Mahmoud, M., 2021. Review of iron sulfide scale removal and inhibition in oil and gas wells: Current status and perspectives. *Energy & Fuels*, 35(18), pp.14401-14421.
33. Mubarak, G., Verma, C., Barsoum, I., Alfantazi, A. and Rhee, K.Y., 2023. Internal corrosion in oil and gas wells during casings and tubing: Challenges and opportunities of corrosion inhibitors. *Journal of the Taiwan Institute of Chemical Engineers*, 150, p.105027.
34. Heidersbach, R., 2018. *Metallurgy and corrosion control in oil and gas production*. John Wiley & Sons.
35. Groysman, A., 2017. Corrosion problems and solutions in oil, gas, refining and petrochemical industry. *KOM–Corrosion and Material Protection Journal*, 61(3), pp.100-117.
36. Liao, K., Leng, J., Cheng, Y.F., He, T., He, G., Zhao, S., Liu, X. and Huang, Q., 2022. Effect of H₂S concentrations on corrosion failure of L245NS steel in CO₂-O₂-H₂S system. *Process Safety and Environmental Protection*, 168, pp.224-238.
37. Perez, N., 2024. Electrochemical corrosion. In *Materials Science: Theory and Engineering* (pp. 835-898). Cham: Springer Nature Switzerland.
38. Harsimran, S., Santosh, K. and Rakesh, K., 2021. Overview of corrosion and its control: A critical review. *Proc. Eng. Sci*, 3(1), pp.13-24.
39. Wang, P., Cai, J., Cheng, X., Ma, L. and Li, X., 2022. Inhibition of galvanic corrosion between crystallographic orientations in low alloy steel by grain ultra-refinement. *Materials Today Communications*, 31, p.103742.
40. Bai, J., Sun, C., Wang, C., Shao, Y., Meng, J., Dong, Q., Xue, F. and Chu, C., 2024. Gradient textures induce micro-galvanic corrosion on Mg. *Journal of Alloys and Compounds*, 1005, p.176119.
41. Ezuber, H. and Zakir Hossain, S.M., 2023. A review of corrosion failures in shell and tube heat exchangers: roots and advanced counteractive. *Heat and Mass Transfer*, 59(6), pp.971-987.
42. Yang, L. ed., 2020. *Techniques for corrosion monitoring*. Woodhead Publishing.
43. Faes, W., Lecompte, S., Ahmed, Z.Y., Van Bael, J., Salenbien, R., Verbeken, K. and De Paepe, M., 2019. Corrosion and corrosion prevention in heat exchangers. *Corrosion reviews*, 37(2), pp.131-155.
44. Islam, M.A. and Farhat, Z., 2017. Erosion-corrosion mechanism and comparison of erosion-corrosion performance of API steels. *Wear*, 376, pp.533-541.
45. Ayyagari, A., Hasannaemi, V., Grewal, H.S., Arora, H. and Mukherjee, S., 2018. Corrosion, erosion and wear behavior of complex concentrated alloys: a review. *Metals*, 8(8), p.603.
46. Wasim, M. and Djukic, M.B., 2022. External corrosion of oil and gas pipelines: A review of failure mechanisms and predictive preventions. *Journal of Natural Gas Science and Engineering*, 100, p.104467.
47. Sanidanesh, Z., 2024. Microbial induced corrosion (MIC) effects on wastewater treatment plant infrastructures.
48. Wu, M., Wang, T., Wu, K. and Kan, L., 2020. Microbiologically induced corrosion of concrete in sewer structures: A review of the mechanisms and phenomena. *Construction and Building Materials*, 239, p.117813.
49. Telegdi, J., Shaban, A. and Trif, L., 2017. Microbiologically influenced corrosion (MIC). *Trends in oil and gas corrosion research and technologies*, pp.191-214.
50. Wang, J., Du, M., Li, G. and Shi, P., 2022. Research progress on microbiological inhibition of corrosion: A review. *Journal of Cleaner Production*, 373, p.133658.
51. Durrani, F., Wesley, R., Srikandarajah, V., Eftekhari, M. and Munn, S., 2020. Predicting corrosion rate in chilled HVAC pipe network: coupon vs linear polarisation resistance method. *Engineering Failure Analysis*, 109, p.104261.
52. Googan, C., 2021. The cathodic protection potential criteria: Evaluation of the evidence. *Materials and Corrosion*, 72(3), pp.446-464.
53. Kagarise, C., Moore, N., Eckert, R. and Kotu, S.P., 2021, April. Advances in Coupon Analysis for Improved Corrosion Management. In *NACE CORROSION* (p. D101S043R002). NACE.
54. Khan, A., Qurashi, A., Badeghaish, W., Noui-Mehidi, M.N. and Aziz, M.A., 2020. Frontiers and challenges in electrochemical corrosion monitoring: surface and downhole applications. *Sensors*, 20(22), p.6583.
55. Soleymani, F., 2023. Internal corrosion monitoring of pipelines using electrochemical techniques: A Comprehensive Review. *Protection of Metals and Physical Chemistry of Surfaces*, 59(5), pp.1045-1061.
56. Sheetal, Kundu, S., Thakur, S., Singh, A.K., Singh, M., Pani, B. and Saji, V.S., 2025. A review of electrochemical techniques for corrosion monitoring—fundamentals and research updates. *Critical Reviews in Analytical Chemistry*, 55(1), pp.161-186.
57. Zhang, C., Amietszajew, T., Li, S., Marinescu, M., Offer, G., Wang, C., Guo, Y. and Bhagat, R., 2022. Real-time estimation of negative electrode potential and state of charge of lithium-ion battery based on a half-cell-level equivalent circuit model. *Journal of Energy Storage*, 51, p.104362.
58. Nölle, R., Beltrop, K., Holtstiege, F., Kasnatscheew, J., Placke, T. and Winter, M., 2020. A reality check and tutorial on electrochemical characterization of battery cell materials: How to choose the appropriate cell setup. *Materials Today*, 32, pp.131-146.
59. Wright, R.F., Lu, P., Devkota, J., Lu, F., Ziomek-Moroz, M. and Ohodnicki Jr, P.R., 2019. Corrosion sensors for structural health monitoring of oil and natural gas infrastructure: A review. *Sensors*, 19(18), p.3964.
60. Cristello, J.B., Yang, J.M., Hugo, R., Lee, Y. and Park, S.S., 2023. Feasibility analysis of blending hydrogen into natural gas networks. *International Journal of Hydrogen Energy*, 48(46), pp.17605-17629.
61. Wang, Y., Song, F., Feng, Q., Qiao, W., Dong, S., Jiang, Y. and Ma, Q., 2024. Basic Theory and Applications of Oil and Gas Pipeline Non-Destructive Testing Methods. *Energies*, 17(24), p.6366.
62. Acquah, S.A., 2021. Assessing the conventional Non-Destructive Testing methods used for the inspection and testing of welded joints in fuel pipelines. University of Johannesburg (South Africa).

63. Eason, T.J., 2017. Ultrasonic thickness structural health monitoring of steel pipe for internal corrosion (Doctoral dissertation, Iowa State University).
64. Zang, X., Xu, Z.D., Lu, H., Zhu, C. and Zhang, Z., 2023. Ultrasonic guided wave techniques and applications in pipeline defect detection: A review. *International Journal of Pressure Vessels and Piping*, 206, p.105033.
65. Vasagar, V., Hassan, M.K., Abdullah, A.M., Karre, A.V., Chen, B., Kim, K., Al-Qahtani, N. and Cai, T., 2024. Non-destructive techniques for corrosion detection: A review. *Corrosion Engineering, Science and Technology*, 59(1), pp.56-85.
66. Chen, P., Li, R., Jia, G., Lan, H., Fu, K. and Liu, X., 2023. A decade review of the art of inspection and monitoring technologies for long-distance oil and gas pipelines in permafrost areas. *Energies*, 16(4), p.1751.
67. Kishizada, T., 2022. Development Of Ultrasonic Measuring Devices (Sensors) That Determine The Level Of Liquid In Tanks (Master's thesis, Khazar University (Azerbaijan)).
68. Aldaher, M., 2021. Resilience-Based Maintenance: a new concept for subsea oil and gas industry (Master's thesis, NTNU).
69. Parlak, B.O. and Yavasoglu, H.A., 2023. A comprehensive analysis of in-line inspection tools and technologies for steel oil and gas pipelines. *Sustainability*, 15(3), p.2783.
70. Ma, Q., Tian, G., Zeng, Y., Li, R., Song, H., Wang, Z., Gao, B. and Zeng, K., 2021. Pipeline in-line inspection method, instrumentation and data management. *Sensors*, 21(11), p.3862.
71. Ho, M., El-Borgi, S., Patil, D. and Song, G., 2020. Inspection and monitoring systems subsea pipelines: A review paper. *Structural Health Monitoring*, 19(2), pp.606-645.
72. Bahadori, A., 2016. Oil and gas pipelines and piping systems: Design, construction, management, and inspection. Gulf Professional Publishing.
73. Groysman, A., 2019. Nondestructive testing and corrosion monitoring. *Non-Destructive Evaluation of Corrosion and Corrosion-assisted Cracking*, pp.261-409.
74. Dhandha, K.H., 2020. Shut down inspection requirements in oil and gas refineries. *Proceedings of the NDE*.
75. Saleh, H. and Hassan, A.I. eds., 2024. *Gamma Rays-Current Insights*. BoD-Books on Demand.
76. Yee, T.S., Shrifan, N.H., Al-Gburi, A.J.A., Isa, N.A.M. and Akbar, M.F., 2022. Prospect of using machine learning-based microwave nondestructive testing technique for corrosion under insulation: A review. *IEEE Access*, 10, pp.88191-88210.
77. Siang, T.W., Firdaus Akbar, M., Nihad Jawad, G., Yee, T.S. and Mohd Sazali, M.I.S., 2021. A past, present, and prospective review on microwave nondestructive evaluation of composite coatings. *Coatings*, 11(8), p.913.
78. Vasagar, V., Hassan, M.K., Abdullah, A.M., Karre, A.V., Chen, B., Kim, K., Al-Qahtani, N. and Cai, T., 2024. Non-destructive techniques for corrosion detection: A review. *Corrosion Engineering, Science and Technology*, 59(1), pp.56-85.
79. Ma, Q., Tian, G., Zeng, Y., Li, R., Song, H., Wang, Z., Gao, B. and Zeng, K., 2021. Pipeline in-line inspection method, instrumentation and data management. *Sensors*, 21(11), p.3862.
80. Peng, X., Anyaoha, U., Liu, Z. and Tsukada, K., 2020. Analysis of magnetic-flux leakage (MFL) data for pipeline corrosion assessment. *IEEE Transactions on Magnetics*, 56(6), pp.1-15.
81. Sathappan, N., 2022. Magnetic Flux Leakage techniques for detecting corrosion of pipes (Doctoral dissertation, London South Bank University).
82. Sharif, N.A., Ramli, R., Nuawi, M.Z. and Mohamed, A.Z., 2020. Theory and development of magnetic flux leakage sensor for flaws detection: A review. *J. Kejuruter*, 32, pp.385-395.
83. Kim, H.M., Rho, Y.W., Yoo, H.R., Cho, S.H., Kim, D.K., Koo, S.J. and Park, G.S., 2012, August. A study on the measurement of axial cracks in the magnetic flux leakage NDT system. In *2012 IEEE International Conference on Automation Science and Engineering (CASE)* (pp. 624-629). IEEE.
84. Harris, C. and Williamson, T.D., 2012, November. Assessing mechanical damage using multiple data sets in inline inspection. In *Proceedings of the Pigging Products and Services Association (PPSA) Seminar Papers*, Aberdeen, UK (Vol. 14).
85. Pham, H.Q., Tran, B.V., Doan, D.T., Pham, Q.N., Kim, K., Kim, C., Terki, F. and Tran, Q.H., 2018. Highly sensitive planar Hall magnetoresistive sensor for magnetic flux leakage pipeline inspection. *IEEE Transactions on Magnetics*, 54(6), pp.1-5.
86. Chen, L., Que, P., Huang, Z. and Jin, T., 2005. Three-dimensional finite element analysis of magnetic flux leakage signals caused by transmission pipeline complex corrosion. *Journal of the Japan Petroleum Institute*, 48(5), pp.314-318.
87. Okolo, C.K. and Meydan, T., 2018. Pulsed magnetic flux leakage method for hairline crack detection and characterization. *AIP Advances*, 8(4).
88. Mao, B., Lu, Y., Wu, P., Mao, B. and Li, P., 2014. Signal processing and defect analysis of pipeline inspection applying magnetic flux leakage methods. *Intelligent Service Robotics*, 7, pp.203-209.
89. Carvalho, A.A., Rebello, J.M.A., Sagrilo, L.V.S., Camerini, C.S. and Miranda, I.V.J., 2006. MFL signals and artificial neural networks applied to detection and classification of pipe weld defects. *Ndt & E International*, 39(8), pp.661-667.
90. Ma, Z. and Liu, H., 2007, September. Pipeline defect detection and sizing based on MFL data using immune RBF neural networks. In *2007 IEEE Congress on Evolutionary Computation* (pp. 3399-3403). IEEE.
91. Layouni, M., Hamdi, M.S. and Tahar, S., 2017. Detection and sizing of metal-loss defects in oil and gas pipelines using pattern-adapted wavelets and machine learning. *Applied Soft Computing*, 52, pp.247-261.

92. Ji, F., Sun, S., Wang, C., Zhang, H. and Liu, D., 2010. Applications of adaptive fuzzy lifting wavelet transform in MFL signal processing. *Insight-Non-Destructive Testing and Condition Monitoring*, 52(1), pp.16-19.
93. Mukherjee, D., Saha, S. and Mukhopadhyay, S., 2012. An adaptive channel equalization algorithm for MFL signal. *NDT & E International*, 45(1), pp.111-119.
94. Huang, S. and Wang, S., 2016. *New technologies in electromagnetic non-destructive testing*. Singapore: Springer Singapore.
95. Zhao, Y., Yan, W., Sun, J., Zhou, M., Meng, Z., Zhao, Y., Yan, W., Sun, J., Zhou, M. and Meng, Z., 2021. Principle and Analysis of EMS: EFT Mechanism and Protection. *Electromagnetic Compatibility: Principles and Applications*, pp.181-205.
96. Husby, K., Myrvoll, T.A. and Knudsen, O.Ø., 2019, March. Eddy Current duplex coating thickness Non-Destructive Evaluation augmented by VNA scattering parameter theory and Machine Learning. In *2019 IEEE Sensors Applications Symposium (SAS)* (pp. 1-6). IEEE.
97. Ciaburro, G. and Iannace, G., 2022. Machine-learning-based methods for acoustic emission testing: A review. *Applied Sciences*, 12(20), p.10476.
98. Li, Y., Bai, Z., Xing, L., Zhang, Q., Ding, S., Zhang, Y., Gao, P., Yu, Z. and Xu, D., 2024. Corrosion monitoring techniques in subcritical and supercritical water environments. *Applied Sciences*, 14(6), p.2350.
99. Nazarchuk, Z., Skalskyi, V. and Serhiyenko, O., 2017. *Acoustic emission. Foundations of Engineering Mechanics*.
100. Pollock, A.A., 2018. Acoustic emission inspection. In *Nondestructive evaluation of materials* (pp. 360-379). ASM international.
101. Ciaburro, G. and Iannace, G., 2022. Machine-learning-based methods for acoustic emission testing: A review. *Applied Sciences*, 12(20), p.10476.
102. Sheikh, M.F., Kamal, K., Rafique, F., Sabir, S., Zaheer, H. and Khan, K., 2021. Corrosion detection and severity level prediction using acoustic emission and machine learning based approach. *Ain Shams Engineering Journal*, 12(4), pp.3891-3903.
103. Zamarréno, C.R., Rivero, P.J., Hernaez, M., Goicoechea, J., Matías, I.R. and Arregui, F.J., 2015. Optical sensors for corrosion monitoring. *Intelligent coatings for corrosion control*, pp.603-640.
104. Al-Shaikhli, F., O'Sullivan, M. and Hui, R., 2023. Fiber-Specific Electrostriction Response Under Intensity Modulation. *Journal of Lightwave Technology*, 41(18), pp.6081-6087.
105. Wen, C., Hu, S., Wang, J., Fang, H. and Xue, X., 2024. Fiber optic sensing technology in underground pipeline health monitoring: a comprehensive review. *Structural Health Monitoring*, p.14759217241280904.
106. Pereira, L., Sousa, I., Mesquita, E., Cabral, A., Alberto, N., Diaz, C., Varum, H. and Antunes, P., 2024. FBG-Based Accelerometer for Buried Pipeline Natural Frequency Monitoring and Corrosion Detection. *Buildings*, 14(2), p.456.
107. Hussain, M., Zhang, T., Jamil, I., Soomro, A.A. and Hussain, I., 2024. Application of machine learning approaches to prediction of corrosion defects in energy pipelines. *Advances in Corrosion Modelling*, pp.127-166.
108. Salem, A.M., Yakoot, M.S. and Mahmoud, O., 2022. Addressing diverse petroleum industry problems using machine learning techniques: literary methodology— spotlight on predicting well integrity failures. *ACS omega*, 7(3), pp.2504-2519.
109. Mathew, C. and Adu-Gyamfi, E., 2024. A review on AI-driven environmental-assisted stress corrosion cracking properties of conventional and advanced manufactured alloys. *Corrosion Engineering, Science and Technology*, p.1478422X241276727.
110. Mohamed Almazrouei, S., Dweiri, F., Aydin, R. and Alnaqbi, A., 2023. A review on the advancements and challenges of artificial intelligence-based models for predictive maintenance of water injection pumps in the oil and gas industry. *SN Applied Sciences*, 5(12), p.391.
111. Atha, D.J. and Jahanshahi, M.R., 2018. Evaluation of deep learning approaches based on convolutional neural networks for corrosion detection. *Structural Health Monitoring*, 17(5), pp.1110-1128.
112. Nash, W., Zheng, L. and Birbilis, N., 2022. Deep learning corrosion detection with confidence. *npj Materials degradation*, 6(1), p.26.