Advances in Corrosion Monitoring Techniques

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Abstract

Corrosion is an industrially and economically challenging environmental material degradation process that has a profound impact on human lives, with a staggering annual global cost of about 2.5 trillion dollars. Corrosion monitoring is a management practice of strategically averting corrosion harm to safeguard tangible assets.This chapter presents a review report on the general advantages of corrosion monitoring as well as the principles, advantages, and disadvantages of the various up- to-date monitoring techniques and kinds of facilities that are used for monitoring, providing insights into the advanced and emerging monitoring technologies. The report shows that, presently, there are several different corrosion monitoring techniques and more in emergence that may not be equally beneficial for every application, so it is essential to carefully evaluate, select, and implement them to effectively track the corrosion processes of assets across different environmental conditions. It is crucial for all structural assets, especially those with various corrosion rates at different surface locations and that are made of metallic and/or non-metallic components such as steel, aluminum, concrete, ceramics, and glass in corrosive settings. Corrosion monitoring is essential for assets that require total removal, repair, or replacement. Corrosion monitoring is purposed to proactively identify potential corrosion risks and take necessary measures to ensure the integrity of our assets and safe working environments. Artificial intelligence, with machine learning capabilities, stands out as an emerging technology with the potential to transform corrosion monitoring and control to previously unachievable levels with traditional monitor- ing techniques.

Keywords: corrosion risks, corrosion management, corrosion monitoring, benefits, techniques, selection, advanced technologies, advantages

1. Introduction

Corrosion is an industrially and economically expensive environmental material- degradation process that has a multifaceted impact on every person, community, country, and the entire world, with a monumental total estimated annual global cost of 2.5 trillion dollars, equivalent to about 3.4% of the global gross domestic product

annually [1]. The corrosion management policy offers a methodical framework for identifying corrosion-related hazards as well as for creating and implementing effec- tive risk control measures. The benefits that can be attained by effective corrosion management include reduced leaks, increased plant availability, decreased unsched- uled maintenance, decreased deferral costs, and statutory or corporate compliance with safety, health, and environmental laws [2, 3]. The corrosion management process offers the focus and action plan details on how to best use human, capital, and material resources to [2]:

i. Reduce corrosion maintenance and repair costs for corroded materials, the quantity of products lost due to corrosion damage, and extend the useful life of manufactured products or assets.

ii. Analyze risk and responsibility by metal type, and examine appropriate metal parts processing and handling guidelines by assessing present risks in produc- tion, shipping, storage, and processing; figuring out the repercussions of failures in each area; and lowering risk by using new packaging and corrosion protection technologies.

iii. Examine the potential for new coatings, alloys, and corrosion inhibitors by implementing best practices and innovative corrosion protections and preventa- tives for more corrosion-resistant goods.

iv. Examine every step of the manufacturing and delivery processes to cover the entire range of corrosion control for improved corrosion protection.

Corrosion management includes choosing the right materials, applying protec- tive coatings, using cathodic protection, adding inhibitors, and conducting regular inspections, etc. for structural systems [3, 4]. All corrosion protection actions are supported by corrosion monitoring data to take early action against all corrosion issues. Corrosion monitoring is therefore a crucial corrosion management process of gathering, observing, and assessing data on the degree of corrosion-induced degrada- tion in a material such as metal, concrete, wood, etc., or the corrosivity of the envi- ronment surrounding the material to know the levels of their degradation through specific corrosion-probing techniques or devices in infrastructures, plants, buildings, bridges, and other engineered systems [2–5]. Usually changes in corrosion rates are used to evaluate the level of degradation of materials, but changes in several other parameters, such as weight loss, mechanical properties, physical properties, chemical properties, and integrity loss of material, such as esthetic value and cracking, are also used in evaluating degradations of materials [6, 7]. Corrosion monitoring can help in several other ways, such as [3, 4, 6–9]:

i. Determining corrosion rates, identifying potentially hazardous conditions, locating structural defects, and discovering material non-compliances.
ii. Providing an early warning that damaging process conditions exist.
iii. Diagnosing a particular corrosion problem and identifying its cause.
iv. Evaluating the effectiveness of a corrosion control or prevention technique.

v. Determining optimal application of corrosion control or prevention technique.

vi. Providing management information relating to the maintenance requirements and ongoing condition of the plant.

vii. Providing performance data and a basis for life prediction.

Corrosion monitoring is usually applied where:

i. High-pressure, high-temperature, flammable, explosive, and toxic processes exist.

ii. There is a high probability of corrosivity in equipment.

iii. Corrosion rate may have changed due to changes in operating conditions.

iv. Corrosion inhibitors are in use.

v. There is a high concentration of corrosive constituents in the process.

vi. Process feedstock is changed.

vii. Plant output or operating parameters are changed from design specifications.

viii. Evaluation of corrosion behavior of alloys is necessary.

ix. Induced potential shifts are used to protect systems and/or structures.

x. There is a vital concern about product contamination due to corrosion.

Almost any industry where corrosion prevention is a top priority can benefit from corrosion monitoring. Examples include the oil and gas sector, such as in pipelines, vessels, flowlines, gathering systems, water wash systems, drilling mud systems, desalters, chemical injection systems, processing, and water systems; the refining sector, such as in crude overheads, sour water strippers, cooling systems, amine systems, and vacuum towers; the pulp and paper sector, such as in boiler systems, digesters, and white liquor; utilities, which include effluent systems, boiler water systems, cooling systems, and make-up water systems; and the petrochemicals or other chemicals/processing sectors, such as in cooling systems and process systems. There are several methods of corrosion techniques, and two or more of the techniques are usually integrated in corrosion monitoring systems to offer a broad foundation for data collection. The alloy system, operational parameters, and actual process fluid all affect the precise techniques that can be employed [9–12].

The aim in this chapter is to provide knowledge advances from credible literary sources on corrosion monitoring techniques, with regards to the different monitor- ing techniques, types of facilities or equipment in use for corrosion monitoring, the techniques' applicability to different environmental settings, the overall advantages of corrosion monitoring, and where corrosion monitoring is needful, with insights into emerging technologies.

2. Methodology

The information in this chapter was compiled, condensed, and refined for improved readability and comprehension using a variety of journals, theses, and other credible literary sources published between 2012 and 2025.

2.1 Corrosion monitoring techniques

Corrosion monitoring techniques are classified as direct or indirect techniques. Direct techniques refers to approaches that measure corrosion rates or associated parameters directly on the surface of the material. These methods provide informa- tion regarding the corrosion process in real-time or almost real-time. Some of the popular direct methods for corrosion monitoring include [10–19]:

2.1.1 Visual monitoring

In this technique, physical inspection by personnel for corrosion is carried out, either without or with various aids such as dyes, magnification, borescopes, etc. to improve visibility. The advantages of the technique are that it is simple, relatively quick, and can be done during regular maintenance. The drawbacks of the technique are that it only detects corrosion after sufficient amounts of corrosion products form, access is required for personnel to the system or part under corrosion, there is the possibility of not detecting corrosion that is hidden by dirt and overlapping parts, and it does not offer continuous monitoring [13–17].

2.1.2 Weight loss coupons

Weight loss coupons are standardized test samples used to evaluate the effects of corrosion on metals or alloys under certain conditions. These coupons are usu- ally flat, small, and rectangular in shape. They are made of the same material as the
metal under evaluation and are exposed to the same environmental conditions as the building or equipment they represent. The type and rate of corrosion that occurs in a system can be monitored and measured using corrosion coupons. By placing the coupons in a field or laboratory test environment, the material's corrosion as repre- sented by the coupons in the environment can be acquired. Corrosion coupons are
often positioned in a system's specific section, such as a vessel or pipeline, and usually left there for a set period of time, which could be a few weeks or several months. After the exposure period, the corrosion coupons are removed and inspected to determine the kind of corrosion and its extent by evaluating variables such as surface morphol- ogy, weight loss, or modifications in material properties. The benefits of the weight loss coupons technique are that it is simple and

inexpensive; it can be used in any environment, including gases, liquids, solids, and particulate flow; corrosion deposits can be seen and examined; visual inspection can be carried out; weight loss and corrosion rate can be easily calculated; inhibitor performance can be easily evaluated; and localized corrosion can be marked and measured. Because weight loss coupons can be made from any commercially available alloy, this method is incredibly flexible. Additionally, a wide range of corrosion phenomena, such as stress-assisted corrosion, bimetallic (galvanic) corrosion, differential aeration, and heat-affected zones, can be explored with the use of suitable geometric designs. They provide a trustworthy way to confirm the efficacy of corrosion prevention methods like the use of coatings and

inhibitors. The drawbacks of the weight loss technique are that it is time-consuming, as it requires lengthy exposure times, and its inability to provide real-time data.
Furthermore, results from this technique are often delayed since the weight loss coupons need to be retrieved and examined in a laboratory, and the technique does not identify localized or early-stage corrosion; instead, it merely offers an average cor- rosion rate across the exposure period of the coupons [10–19].

2.1.3 *Electrical resistance monitoring*

This monitoring technique uses variations in a metal's electrical resistance to determine how quickly it is corroding. This method requires direct touch with the metal surface. This method involves conducting intrusive electrical resistance monitoring by inserting tiny metal probes or electrodes into the system or piece of equipment under observation. These probes are made of the same material as the metal under evaluation. Surface alterations caused by corrosion result in variations in electrical resistance. The electrical resistance of the probes is regularly measured using advanced technology. By keeping an eye on these resistance changes, corrosion severity and pace can be determined. Higher numbers indicate less corrosion, whilst
lower resistance levels suggest a higher rate of corrosion. Intrusive electrical resistance monitoring enables the early detection of corrosion problems by supplying real-time data on corrosion activity. It is widely used in applications such as storage tanks, pipelines, and critical infrastructure where rapid corrosion reaction and continuous monitoring are crucial. The benefits of coupons are all present in electrical resistance probes. They are available in a wide range of element geometries, metallurgical makes, and sensitivities; they can be flush mounted to perform pigging operations without removing them; they can be used to set off an alarm; they react rapidly to corrosion disturbances and can be used to obtain direct corrosion rates while they are installed in-line until their operational life is over; and their diverse range of sensitivities can allow the operator to select the most sensitive one that is compatible with the needs of the process. Their main drawbacks are sensitivity to temperature changes, which can affect resistance measurements, and limitation to monitoring only uniform or nearly uniform corrosion. They are also less appropriate for short-term corrosion studies since they need prolonged exposure to identify significant corrosion trends [10–19].

2.1.4 *Inductive resistance probes*

These are probes that work by measuring changes in the electrical impedance of metals to determine the corrosion rate. Unlike intrusive probe types, these probes do not need to come into close touch with the metal surface. The electromagnetic
theory underpins the operation of these probes. They are made of a coil that creates a magnetic field around the metal or component that is being monitored. As the metal corrodes, its electrical resistance changes in value and causes changes in the magnetic field. The inductive resistance probe detects these changes and transforms them
into corrosion data. This monitoring technique is particularly useful in situations where physically inserting probes into a system is not practicable nor acceptable. For instance, it is effective in monitoring the rusting of exterior objects like buildings or pipes. Inductive resistance probes identify corrosion activity in real time to enable continuous monitoring. By tracking variations in electrical impedance, it can deter- mine the rate and degree of corrosion. Higher impedance values frequently indicate lower rates of corrosion, while lower values suggest a higher rate [14–19].

2.1.5 *Linear polarization resistance*

In the linear polarization resistance technique, a metal's resistance to corrosion is measured. The technique works on the principle that when little electrical charge
is applied to the metal's surface in a range of E_{corr} ± 25 mV, the current that follows
□ I_{corr} □ is measured using the Stern-Geary relation given by (1) to (3) to help deter- mine the rate of the metal corrosion [12].

2.1.6 *Electrochemical impedance spectroscopy*

Impedance measurements are used in electrochemical impedance spectroscopy, a corrosion monitoring technique for examining the corrosion process of metals. It is a sophisticated technique that offers important insights into corrosion processes and is founded on electrochemical principles. This method involves applying a little alter- nating current at various frequencies to the metal surface. An impedance spectrum is obtained by measuring the electrical response that results. We may learn about a vari- ety of electrochemical activities occurring on the metal surface from this spectrum, including corrosion reactions and protective coating generation. One can ascertain crucial factors like corrosion rate, protective coating integrity, and corrosion inhibitor

efficacy by analyzing the impedance spectrum. Additionally, it can identify localized pitting or corrosion. A flexible method for gathering qualitative and quantitative data on corrosion processes is electrochemical impedance spectroscopy. It enables us to comprehend the intricate behavior of metals in situations that are acidic [15–19].

2.1. / **Electrochemical frequency modulation**

The way metals erode can better be understood by using a corrosion monitoring technique called electrochemical frequency modulation (EFM). A little alternating current is applied to the metal, and the variations in its electrochemical response are monitored. By concentrating on the frequency modulation of the current, EFM enables us to ascertain crucial elements such as the type and pace of corrosion. This method can distinguish between several corrosion types, such as uniform corrosion and localized corrosion, and it offers quantitative data regarding the degree of cor- rosion. The capability of EFM to track corrosion in real time and identify variations in corrosion rate is one of its benefits. This non-destructive technique works well in a variety of settings, such as high-temperature systems and aqueous liquids. EFM is frequently used in both industrial and research contexts to analyze the performance of protective coatings, determine the factors driving corrosion rates, and gauge the efficacy of corrosion inhibitors [12–19].

2.1.8 Harmonic analysis

This technique examines specific signal frequency components to determine how metals deteriorate. This technique finds harmonic frequencies linked to corrosion processes by analyzing the metal's electrical response. Numerous details regarding the rate and intensity of corrosion can be gleaned from the amplitudes and phases of these harmonic components. This method can be used to identify various forms of corrosion, including pitting and localized corrosion, and to monitor how corrosion behavior varies over time. Aqueous liquids, industrial settings, and climatic conditions are just a few of the locations in which this non-destructive method can be applied. In summary, it is a technique for monitoring corrosion that concentrates on particular frequency compo- nents to comprehend the corrosive behavior of metals. It can identify the types and rates of corrosion by examining these components. This non-destructive technique helps assess and enhance corrosion prevention strategies [12–20].

2.1.9 Electrochemical noise

In this technique, the corrosion processes are examined by sporadic variations of the associated electrical impulses from the corrosion processes to know the corrosion status quo of metals. Direct contact with the metal surface is necessary for this tech- nique. Electrodes or probes are inserted into the apparatus or system under observa- tion in order to track electrochemical noise. The tiny electrical impulses produced by metal surface corrosion processes are picked up by these electrodes. The rate of corrosion, localized corrosion, and other significant corrosion-related characteristics can be learned about by examining the random fluctuations in these signals, some- times referred to as electrochemical noise. Corrosion mechanisms and the efficacy of corrosion management techniques can be learned about by examining features such as signal amplitude, frequency distribution, and duration. Localized corrosion can inflict significant damage with modest overall corrosion rates, making electrochemical noise

monitoring particularly useful for identifying and evaluating this type of corrosion. It can be used in a variety of contexts, such as industrial settings, atmospheric condi-
tions, and water solutions, and it offers real-time monitoring capabilities. Although the technique may identify both localized and general corrosion, it is highly costly to set up and run, and results may be distorted by external signal noise sources. The material or system being monitored must be shut down in order to install and retrieve data, and the data received using this technology may be challenging to interpret [10–19].

2.1.10 Galvanic monitoring

In this technique, the instantaneous corrosion current of the metal or alloy is mea- sured using the galvanic monitoring technique, also known as zero resistance ammetry (ZRA). ZRA probes expose the process fluid to two electrodes made of different metals. There is a natural voltage (potential) difference between the electrodes when sub- merged in solution. The rate of corrosion on the more active electrode pair is correlated with the current produced by this potential difference. The electrode pairs for bimetallic corrosion, pitting and crevice attack, corrosion-assisted cracking, corrosion by highly oxidizing species, and weld deterioration can all be monitored galvanically. The most common uses for galvanic current measurement are in water injection systems where the concentration of dissolved oxygen is a major concern. Galvanic currents and, thus, the rate at which steel process components corrode are significantly increased when oxygen seeps into such systems. When gaskets or deaeration systems leak, galvanic monitoring systems can detect the presence of oxygen in the injection waters [10–19].

2.1.11 Potentiodynamic polarization

This is a corrosion monitoring technique in which a metal's resistance to corrosion is evaluated. It entails adjusting the metal's potential while monitoring the relation- ship between its corrosion current and voltage. The metal is usually subjected to various potentials during potentiodynamic polarization, and the currents that result are measured. This obtained information aids in the understanding of the corrosion behavior of the metal. Crucial corrosion characteristics can be ascertained by examin- ing the polarization curve, which illustrates the link between current and potential.
These include the polarization resistance, which shows the metal's capacity to with- stand corrosion, and the corrosion potential, which shows the metal's propensity to corrode. We can assess a variety of corrosion events, including passivation, pitting, and general corrosion, using potentiodynamic polarization. It offers insights into the efficacy of corrosion control techniques and assists in identifying critical potentials where corrosion is likely to occur [10–19].

2.1.12 Thin layer activation and gamma radiography

In this technique, radioactive substances are utilized to evaluate the structural integrity and corrosion of material components. The process of thin-layer activation involves applying a thin coating of a radioactive substance to the surface of the material component. Radiation from this radioactive substance reacts with the material com- ponent and the byproducts of corrosion. The amount and location of corrosion on the material's surface can then be ascertained by measuring the radiation that is released.

In contrast, gamma radiography uses a gamma ray source to examine the interior structure of the material component. Any interior corrosion or degradation can beidentified through measurement of the transmitted gamma rays intensity passing through the material component. Both gamma radiography and thin-layer activation can provide detailed internal structural images of material components. Gamma radi- ography enables interior corrosion or degeneration to be evaluated; thin layer activa- tion aids in the understanding of surface corrosion. These techniques are particularly helpful for monitoring the progress of localized corrosion in a material component, especially when the component is intricate and difficult to access without causing harm to it. However, these techniques are restricted to only materials that can be penetrated by radiation and call for certain tools and safety measures against radiation [10–19].

2.1.13 Electrical field signature method

This is a non-intrusive technique that assesses the corrosion of a metal without coming into contact with the metal. Rather, it measures and examines the changes in the electrical field brought on by corrosion processes. This technique involves only placing sensors or probes close to the metal surface without making direct contact. The electrical field fluctuations brought on by corrosion reactions occurring on the metal surface are detected and analyzed by these sensors. Crucial details about the type of corrosion, its rate, and even localized corrosion can be learned by examining these electrical field signatures. This method gives information about how the metal is corroding and enables real-time monitoring. The technique is capable of continuous corrosion monitoring using satellite communication. It is appropriate for monitoring pits on huge structures or locations where direct access to the metal surface is chal- lenging due to its non-intrusive nature. It is, however, expensive and labor-intensive to install and cannot detect corrosion pits that are less than 0.8 mm in size [13–19].

Acoustic emission

This is a non-intrusive technique in which noises that material components produce are used to assess how they are corroding. In this technique, sensors or other equip- ment are placed on or near the surface of the material component to capture the sounds made during corrosion. These sounds could be related to cracking, hydrogen leakage, or material deterioration. Many details regarding the corrosion features, including the rate and extent of damage, can be gleaned from the characteristics of these noises, including their frequency, volume, and duration. For the detection and tracking of interior material changes, such as localized degradation, acoustic emission is especially helpful. It is suitable for a variety of materials, including metals, composites, and coatings, and it offers real-time monitoring. On the side of advantages, the technique is non-destructive, can be used on in-service equipment, and provides localized thickness measurements, while its drawbacks are the need to access both material sides and the limitation to monitoring only thickness loss due to corrosion [10–19].

2.1.14 Magnetic flux leakage technique

This is a popular nondestructive technique for detecting corrosion anomalies in pipelines. Steel's magnetic qualities serve as the foundation for the sensing principle. In the absence of defects, magnetic flux lines would primarily flow through the interior of the ferromagnetic material when it is magnetized near saturation under the applied magnetic field; in contrast, bending and leakage of magnetic flux lines will occur at corrosion or defect sites. An electromagnet typically creates the magnetic field, and a Hall-effect sensor is employed to find magnetic flux leakage. The multi- flux leakage technique is limited for material surface and near-surface detection, but it works well for large-area examination. To identify the shapes of faults and differen- tiate between internal and external defects, improvements are required [10–16].

2.1.15 Multi-frequency electromagnetic technique

Another popular non-destructive corrosion monitoring technique is electro- magnetic-based sensing, in which a transmitter coil and a receiver coil make up the sensor. There are numerous variations of this monitoring approach, which is based on Faraday's law of induction. The multi-frequency electromagnetic inspection sensor for pipeline integrity and corrosion detection is one example. The technique works on the principle that an alternating current excites the transmitter coil, and the resulting alternating magnetic field causes eddy currents to flow through the nearby conductive pipes. A voltage with a phase shift from the primary electromagnetic field is induced in the separate reception coil by the transmitter's primary electromagnetic field and a secondary field created by eddy currents in the pipes. The electrical conductivity, magnetic permeability, and defect existence of the material all affect the phase shift and magnitude change. Low-frequency electromagnetic scans can be used to calculate the thickness of pipe metal, while high-frequency electromagnetic scans can distin- guish between inner wall characteristics because of the skin effect [10–16].

2.2 Indirect techniques

Indirect corrosion monitoring techniques are those techniques used to evaluate a material's corrosion behavior in an indirect manner. These techniques rely on second- ary indicators that offer information about the corrosion process rather than directly monitoring corrosion rates or damage. These methods involve measuring things like electrical resistance, weight or size changes, surface roughness or color changes, mechanical property changes, or the propagation of ultrasonic waves. The following are a few indirect methods of corrosion monitoring [13–19]:

2.2.1 Corrosion potential

Corrosion potential is one corrosion monitoring technique that aids in assessing the probability of corrosion on metal surfaces. The corrosion potential is the differ- ence in electrical potential between the metal surface and its surroundings. It is a non-intrusive technique, and it assists in

assessing whether the metal will corrode or
remain safe. To quantify it, we use reference electrodes or other non-contact methods. By monitoring the corrosion potential over time, we may identify any changes that may indicate a higher risk of corrosion or the effectiveness of corrosion prevention strategies. If the corrosion potential shifts toward more positive or negative values, it indicates changes in the metal's corrosion behavior [13–19].**Hydrogen flux monitoring**

This non-invasive method aids in comprehending the amount and behavior of hydrogen gas, which can exacerbate corrosion. To monitor hydrogen flux, sensors or probes are placed near the material surface to identify and measure the flow of hydro- gen gas. These sensors monitor the way hydrogen moves through the material or is released during corrosion. Monitoring the hydrogen flux provides important informa- tion on the presence, concentration, and interactions of hydrogen with the material. This information can be used to evaluate the effectiveness of corrosion control meth- ods and understand the risk of corrosion caused by hydrogen. Hydrogen flow monitor- ing is particularly useful for materials that are vulnerable to hydrogen embrittlement or in environments where hydrogen gas is present, like in the oil and gas industry. This method aids in material selection, design considerations, and the use of preventive measures to lessen the consequences of hydrogen-induced corrosion [12–19].

2.2.2 Chemical analyses

The process of analyzing and assessing the chemical alterations that take place in a corroding system is known as chemical analysis in corrosion monitoring. It
entails researching the chemical makeup of corrosive solutions, examining corrosion byproducts, and determining the many chemicals that contribute to the corrosion process. Chemical analyses use a variety of methods, including [10–21]:

i. **Corrosion product analysis:** Examining the characteristics and nature of the corro- sion products that are produced during corrosion is part of this technique. These products are identified and analyzed using methods such as scanning electron microscopy and X-ray diffraction.

ii. **Electrochemical analysis:** In this technique, electrochemical parameters such as pH, potential, and ion concentration are evaluated in order to determine how a material is affected by the corrosive environment. For electrochemical analysis, techniques like ion chromatography and potentiometry are employed.

iii. **Spectroscopic analysis:** This technique involves the detection and quantitative measurement of certain chemical species or components present in the corrosive environment, using spectroscopic techniques such as atomic absorption spec- troscopy, Raman spectroscopy, and infrared spectroscopy to understand the rate of corrosion that is taking place.

iv. **Wet chemical analysis:** In this technique, the concentration of specific ions or compounds in the corrosive solution is determined using titration techniques and chemical reagents to have insight into the level of corrosion of specific mate- rial components in that corrosive solution. For instance, the concentration of chloride is measured using silver nitrate titration.

2.2.3 Biological monitoring and analysis

This technique generally seeks to identify and quantify the presence of sulfate-reduc- ing bacteria (SRBs), a class of anaerobic bacteria that consume sulfate from the process stream and generate sulfuric acid, a corrosive that attacks production plant materials.

2.2.4 Sand/erosion monitoring

In this technique, specially designed devices are used to measure sands and other slurry particles as well as erosion in a flowing system. The technique finds wide application in oil/gas production systems where particulate matter is present.

2.3 Main equipment or instruments of corrosion monitoring system

The industry, application, and degree of information required for corrosion analy- sis can all affect the equipment utilized in a corrosion monitoring system. Finding the best equipment for a particular monitoring project might be aided by speaking with corrosion specialists or specialized suppliers. The primary components of a corrosion monitoring system include [15–19, 22]:

i. **Corrosion probes/sensors:** These are available in various varieties, including galvanic corrosion probes, corrosion coupons, linear polarization resistance (LPR) probes, and electrochemical noise (EN) probes. They are installed with the purpose of measuring the corrosion rates in the system under observation.

ii. **Data loggers:** These devices gather and store data from the corrosion probes and also keep track of crucial variables like temperature, corrosion rate, humidity, and other environmental factors.

iii. **Transmitters:** A central monitoring system receives the data that the probes or loggers have gathered via transmitters. Depending on the monitoring system, they might be wired or wireless.

iv. **Central Monitoring system:** The data sent by the probes or loggers is received and processed by this system. In order to analyze, visualize, and present the data, it usually consists of hardware and software components. Engineers or operators can monitor corrosion trends, identify anomalies, and decide on maintenance and preventative plans with the aid of the central monitoring system.

v. **Reference electrodes:** To create a reference potential for precise corrosion meas- urements, reference electrodes collaborate with corrosion probes or sensors. Saturated calomel electrodes (SCE) and silver/silver chloride (Ag/AgCl) elec- trodes are common varieties.

vi. *Wiring and cabling*: Reliable connections between the probes, data recorders, transmitters, and the central monitoring system require appropriate wiring and cabling. These parts need to be made to be resistant to corrosion and to endure harsh climatic conditions.

vii. **Power supply:** For corrosion monitoring devices to function, a steady power sup- ply is required. Depending on the particular configuration, batteries, AC power sources, or a combination of both may be used.

viii. **Ancillary equipment:** Depending on the needs and application, more equipment can be needed. For outdoor installations, these can include weatherproof enclosures; mounting brackets or clamps to hold the probes in place; calibration standards for routine sensor calibrations; and coating coupons or protective coatings for reference.

In order to select the most appropriate sensors, a series of evaluation criteria need to be considered.
The main criteria include the following: size suitability for the application need, ruggedness, required depth of scan/in situ loss of section (direct), reliability/

accuracy, life span, coupling/installment, mobility (direct), sensitivity, power con- sumption, the ability of the sensor to function in the requisite environment (aqueous or non-aqueous), and how well the sensor systems and/or component types have worked or not in history as designed for other projects [10–19].

2.4 Importance of corrosion monitoring

Corrosion monitoring is very important for the following reasons [2–19]:

i. Preservation of assets: The structural integrity of many assets, including materi- als, equipment, and structures, is preserved by avoiding significant breakdowns and prolonging their life through timely detection by monitoring and resolving corrosion problems.

ii. Ensuring safety: Failures brought on by corrosion can present major safety risks, especially in sectors like infrastructure, transportation, and oil and gas. Possible corrosion hazards can be proactively detected to take the required actions to guarantee a safe working environment through routine corrosion monitoring.

iii. Cost-efficiency: Costly replacements, repairs, and downtime can result from cor- rosion. Vigilant corrosion monitoring allows us to better plan maintenance tasks, put in place suitable corrosion management strategies, and ultimately reduce the expenses related to major repairs and asset replacements.

iv. Optimizing performance: Equipment and system performance and efficiency are adversely affected by corrosion. We can identify early indicators of deterioration and take corrective measures, such as replacements, repairs, or adjustments, to preserve peak performance by keeping an eye on corrosion levels.

v. Regulatory compliance: Corrosion has a negative impact on the efficiency and performance of systems and equipment. By monitoring corrosion levels, we can see early signs of deterioration and implement remedial actions, such as replace- ments, repairs, or changes, to maintain top performance.

vi. Environmental protection: Hazardous material spills or leaks due to corrosion can endanger the environment. We can find possible leakage sources, stop environ- mental contamination, and lessen the effect on nearby ecosystems by conducting careful corrosion monitoring. In conclusion, corrosion monitoring is essential
for maintaining asset integrity, guaranteeing safety, cutting expenses, improving performance, satisfying legal requirements, and preserving the environment. By taking proactive measures to solve corrosion-related problems, we extend the life of our priceless assets and encourage effective and sustainable operations.

2.5 Advanced methods and emerging technologies

2.5.1 Fiber optics technique

This is an advanced method of corrosion monitoring by which temperature, strain, and corrosion-related alterations in the structure of assets are measured using opti- cal fiber sensors. These sensors detect changes in light transmission brought on by

expansion, contraction, or chemical reactions from corrosion, among other changes in the material's properties. Structural health is monitored using a variety of designs, such as Distributed Optical Fiber Sensors (DOFS) and Fiber Bragg Gratings (FBG) [23–32].
The advantages of the fiber optic sensor technique are high sensitivity, real-time monitoring, and minimal maintenance requirements since fiber optic sensors are immune to electromagnetic interference, making them highly reliable in offshore environments where electronic noise can affect conventional sensors. In addition, fiber optic sensors can cover long distances, allowing for extensive structural monitoring with a single fiber network. In comparison to electrical-based sensors, fiber optic sen- sors are also non-destructive, have in-situ distributive measurements, long reach, small size, flexibility, geometric versatility, and light-weight, and are inherently immune to electromagnetic interference. They are also compatible with optical fiber data com- munication systems and safer when flammables are present. The limitations of the technique are that fiber optic sensors have high installation costs and require special- ized expertise for deployment and data interpretation. Moreover, the complexity of integrating these sensors into existing infrastructure of assets can pose challenges, and physical damage to fiber optics can lead to signal loss or degradation [23–32].

2.5.2 Wireless corrosion monitoring

Wireless sensors are used by wireless corrosion monitoring systems to send corrosion data to a central monitoring station. In remote or dangerous settings where wired systems are unfeasible, these technologies are especially helpful. Benefits of the technology include low installation cost, the capacity to deliver real-time data from distant locations, and the elimination of the need for significant wiring. Additionally, the wireless capability enables monitoring in inaccessible locations. Passive wireless sensors are inexpensive and small enough to be widely used in the system of interest. Its drawbacks include the need for battery-operated sensors, which may not last very long, and the possibility of signal interference in specific settings [29–37].

2.5.3 Corrosion monitoring with IoT

In this technology, Internet of Things (IoT)-based systems, utilizing a network of wireless sensors, cloud computing, and data analytics, remotely monitor corro- sion variables in real time. These devices wirelessly send data to a central monitoring unit on environmental factors such as temperature, humidity, and salinity, as well as
structural health indicators like metal loss and electrochemical activity. It is then pos- sible to use machine learning algorithms to identify patterns and anticipate possible malfunctions. This corrosion monitoring technology has the following benefits: it sup- ports predictive maintenance by identifying corrosion risks before significant damage occurs, optimizing maintenance schedules, and minimizing operational disruptions; it provides remote accessibility, enabling engineers and managers to monitor asset structures from any location via cloud-based dashboards and mobile applications; and it enables continuous, real-time monitoring, reducing the need for manual inspections and downtime while offering predictive analytics for proactive corrosion manage- ment; and it enhances data accuracy and integration by combining multiple sensor inputs, offering a comprehensive view of corrosion progression. However, the technol- ogy has some drawbacks because it needs a dependable way to send data, which can
be hard to achieve in environments with poor connectivity; connecting it to existing digital systems might need a lot of money and technical know-how; the sensors and communication parts must be tough enough to withstand harsh environmental condi- tions, raising the initial costs; setting up and integrating it can be difficult; and strong cybersecurity measures are needed to keep the data safe

2.5.4 Corrosion monitoring using artificial intelligence

Artificial intelligence is the equipment of computer system to mimic human capa- bility by reacting intelligently in making decisions to solve problems on its own with- out or with minimal human intervention. The main objectives of artificial intelligence research include robotics, general intelligence, vision, automated planning, natural language processing, and knowledge representation. Deep learning, pattern recogni- tion, neural networks, expert systems, evolutionary computation, machine learning, and discriminant analysis, metaheuristic optimization, swarm optimization, video processing, and computer vision are just a few of the artificial intelligence fields that have been in use especially for some research [38]. The different intelligence methods and their relationships are shown in [38] The most reliable and successful methods in corrosion engineering among such technologies are machine learning, deep learning, and pattern recognition. The use of artificial intelligence (AI) and machine learning to evaluate corrosion data and forecast corrosion behavior is growing. The advantages of applying AI in corrosion monitoring include the following [36, 39–43]:

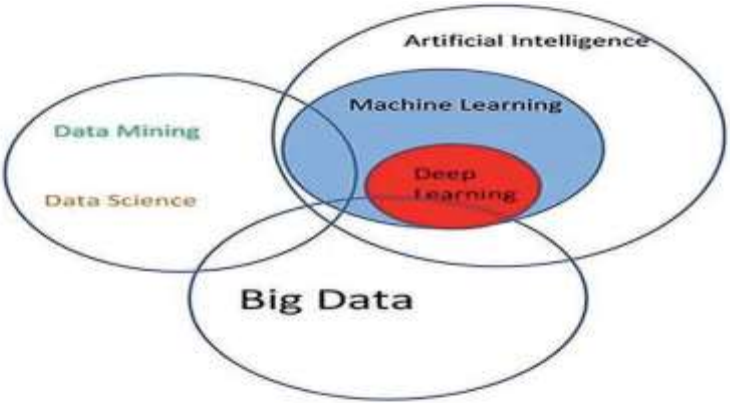

Figure 1.
Artificial intelligence techniques interrelation [38].

i. Capability of generating accurate predictive models of corrosion behavior based on environmental variables such as temperature, pressure, and chemical composition for greater understanding of corrosion mechanisms and forecasting of effects under various circumstances.

ii. AI-powered systems can continuously monitor corrosion signs in real-time for early diagnosis of corrosion-related problems.

iii. AI-driven warning systems integrated with IoT sensor networks can deliver immediate notifications, facilitating prompt action and intervention when anomalous corrosion-related circumstances are identified.

iv. Capability to identify tiny corrosion patterns that people might miss, like com- plex or localized types that could lead to rapid deterioration.

v. Large datasets from multiple sources (sensors, laboratory tests, and historical records) can be analyzed by AI algorithms, especially machine learning and deep learning, to find intricate patterns and relationships suggestive of corrosion. This allows for more precise predictions of corrosion rates and possible failures.

vi. AI in corrosion monitoring has several other benefits, including increased preci- sion in corrosion rate prediction, early failure risk identification via real-time sensor data processing, and optimized maintenance plans, all of which reduce costs and increase safety of assets.

Although artificial intelligence with its machine learning capability holds promise for overcoming the shortcomings of traditional corrosion monitoring techniques by its ability to analyze vast amounts of data, spot patterns, and produce projections, the drawbacks of the technology are that it necessitates knowledge of data science and artificial intelligence, as well as vast datasets for training machine learning models [36, 38–42].

3. Conclusion

A review report on advances in corrosion monitoring techniques has been pre- sented, covering their pros and cons, areas of application, and overall advantages. The report shows that there are many corrosion monitoring techniques, and many more are emerging, and the application of any technique will depend on the accuracy level and reliability needed for specific applications, the type of corrosion, the environ- mental conditions, cost affordability, the level of automation involved, and monitor- ing capacity and speed. The review report shows that:

i. Corrosion monitoring is a crucial aspect of the corrosion control strategy in various industries. By measuring and analyzing corrosion-related parameters through corrosion monitoring, organizations can assess the extent of corrosion, predict its progression, and implement appropriate control measures.

ii. The classical corrosion monitoring devices include weight-loss coupons, spool pieces, electrical resistance probes, linear polarization probes, galvanic probes, hydrogen pressure probes, hydrogen electrochemical patch probes, electrochem- ical noise probes, and the field signature method, but all these techniques, while

useful, have limitations. The various limitations of these techniques include sensitivity limitation, potential for missed issues, scope limitation, inaccessibil- ity challenges to the system or part being monitored, difficulty in monitoring localized corrosion, time-consuming and laborious processes, expertise require- ments for accuracy, difficulty in real-time monitoring, and potential for some undetected corrosion and catastrophic failures.

iii. To address limitations of classical or traditional corrosion monitoring tech- niques, advanced or emerging corrosion monitoring technologies such as electrochemical probes, acoustic emission monitoring, fiber optic sensors, wireless IoT-based remote sensing systems, and artificial intelligence are now being considered. These techniques or technologies offer real-time data acquisi- tion, higher sensitivity, and predictive maintenance capabilities, allowing for proactive corrosion management and risk mitigation. Industries can therefore better reduce the financial and safety risks related to corrosion and guarantee the longevity and functionality of their assets by investing in cutting-edge corrosion monitoring systems and procedures.

iv. Although the focus is now on cutting-edge corrosion monitoring systems and procedures, especially artificial intelligence, there are still issues with cost, system integration, and environmental adaptation, requirement of expertise personnel, etc. Future studies in these technologies of corrosion monitoring should therefore concentrate on: advancing wireless and energy-efficient sen- sor networks to improve real-time monitoring capabilities in remote offshore environments, developing cost-effective sensor technologies that balance afford- ability with high performance, enhancing artificial intelligence-driven predictive models to improve the accuracy of corrosion trend analysis and risk assessment, and enhancing personnel training in these technologies.

Conflict of interest

The authors declare that there are no conflicts of interest regarding this work.

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