INDUSTRIAL CORROSION

Fundamentals, Failure, Analysis and Prevention

Edited By
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Contents

Preface

Corrosion is an invisible force with visible and often catastrophic effects. Across various industrial sectors—ranging from oil and gas to aerospace, automotive, and beyond—corrosion poses serious challenges, both in terms of safety and economic loss. It leads to equipment failures, structural weaknesses, costly downtimes, and environmental hazards. As global industries strive to improve efficiency and safety while reducing costs, understanding corrosion mechanisms and developing effective prevention strategies have become indispensable. This book, *Industrial Corrosion: Fundamentals, Failure, Analysis and Prevention*, is designed to equip professionals and researchers with the knowledge and tools needed to tackle corrosion issues head-on.

The book begins with an explanation of the chemical and electrochemical processes that drive corrosion, setting the stage for a deeper understanding of material degradation. This chapter provides the theoretical foundation needed to grasp why and how corrosion occurs, making it accessible to both seasoned professionals and newcomers in the field.

We then shift focus to the various types of industrial corrosive environments, examining the unique challenges presented by different industries. From the oil and gas industry—where pipelines, refineries, and storage tanks face relentless attack from harsh chemicals and moisture—to the marine and offshore industry, where saltwater and high humidity exacerbate corrosion risks, each environment demands tailored solutions. In power plants, both nuclear and non-nuclear, high temperatures, pressure, and corrosive by-products lead to complex corrosion problems that require specialized materials and preventive techniques.

Moving further, industries such as chemical processing, food and beverage, pulp and paper, and aerospace are discussed in detail, showcasing how corrosion impacts their operations and safety. Each chapter delves into specific corrosion types—such as uniform, pitting, crevice, and stress corrosion cracking—and explores modern solutions, including advanced coatings, inhibitors, and material selections. The chapters on transportation infrastructure and the automotive industry highlight how corrosion affects critical infrastructure and vehicles, areas of immense societal impact.

One of the most critical sections is dedicated to corrosion failures in nuclear power plants, where the stakes are incredibly high. This chapter highlights the complexity and severity of corrosion in the nuclear industry, where even minor material degradation can lead to significant safety and operational concerns. Key to any successful corrosion management strategy is corrosion monitoring and inspection techniques, which are covered in-depth, offering insights into the latest technologies for detecting corrosion early and preventing costly failures. From non-destructive testing methods to real-time monitoring tools, this chapter is essential for industries looking to stay ahead of corrosion risks.

The goal of this book is not just to provide theoretical knowledge, but also to offer practical, actionable insights that professionals can apply directly to their industries. With the combination of fundamental corrosion science, industry-specific challenges, advanced monitoring techniques, and real-world case studies, this book serves as a thorough reference for corrosion engineers, materials scientists, and industrial professionals. It also caters to researchers and students, offering a clear and structured understanding of the complex and evolving world of corrosion.

By addressing corrosion's multifaceted nature and providing strategies to prevent its costly effects, I hope this book helps industries improve safety, reduce operational costs, and enhance the longevity of their assets. As technological advancements continue to evolve, so too must our approaches to corrosion prevention and control. It is my belief that through education, innovation, and collaboration, we can build a future where the impact of corrosion is not just managed but minimized. Finally, our gratitude goes to Martin Scrivener and the team at Scrivener Publishing for their support in bringing this volume to light.

Martin Scrivener and the team at Scrivener Publishing

The Editors
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1

Corrosion Fundamentals: Understanding the Science Behind the Damage

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Abstract

Corrosion, a pervasive and complex phenomenon, significantly impacts industries leading to material degradation, economic losses, and safety hazards. This chapter delves into the fundamental principles of corrosion offering a comprehensive understanding of its underlying science. It explores the chemical mechanisms that drive corrosion examining various types such as uniform corrosion, pitting, galvanic corrosion, stress corrosion cracking, and microbiologically influenced corrosion. Additionally, the chapter outlines the influence of different environmental factors—ranging from atmospheric conditions to industrial pollutants—that exacerbate corrosion processes. Through historical and contemporary perspectives, the chapter underscores the far-reaching economic, environmental, and safety implications of corrosion. It also discusses the evolution of corrosion monitoring techniques in industrial environments emphasizing their importance in predicting material failure, optimizing maintenance, and enhancing operational efficiency. By addressing the multifaceted nature of corrosion, this chapter serves as a foundational guide for understanding and managing this critical issue across industries.

***Keywords*:** Corrosion science, corrosion, degradation, galvanic corrosion, pitting, stress corrosion cracking

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1.1 Introduction

Corrosion has long been a topic of extensive scientific research due to its significant and often devastating consequences. It is generally defined as the deterioration of a material, typically a metal, or its properties as a result of chemical reactions with its environment [1–3]. While traditionally associated with metal oxidation, corrosion now encompasses a broader range of materials, including ceramics, polymers, composites, biomaterials, and nanomaterials. The International Standard Organization (ISO) defines corrosion as the "physicochemical reaction between a material and its environment, leading to modifications in the properties of the material, and often resulting in degradation of the material's function or the function of the system it is part of" [3]. This more inclusive understanding of corrosion reflects the profound technological advancements and diversification of materials used in modern industries.

At its core, corrosion is an inevitable interaction between a material and its surrounding environment. The environment can take many forms—whether gas, liquid, or solid—and includes various physical and chemical factors such as temperature and the composition of substances in contact with the material [1]. Metals, in particular, are prone to corroding because they naturally tend to revert to more stable states, such as oxides, hydroxides, salts, or carbonates [4]. This transformation is governed by thermodynamics, specifically the Law of Entropy, which dictates that metals produced and shaped into their refined forms tend to revert back to their natural ore state (e.g., iron returning to rust). Because of this tendency, pure metals are rarely found in nature, as they readily combine with other elements to form ores.

The scope of corrosion has evolved over time from an obscure area of study to a well-established engineering discipline. Significant strides have been made in understanding and preventing corrosion, but many challenges remain for scientists and engineers. Learned societies, such as NACE International, the European Corrosion Federation, and the Japan Society of Corrosion Engineers, have played a pivotal role in advancing corrosion education and research fostering collaboration among experts and addressing industry-relevant problems [5].

This chapter will explore the brief outline of the fundamental principles of corrosion aiming to provide a comprehensive understanding of this complex phenomenon. By delving into the chemical mechanisms that drive corrosion, readers will gain insights into how and why materials degrade, and how this process can be mitigated or controlled. The chapter serves as an introduction to corrosion science laying the groundwork for understanding both the basic concepts and the advanced approaches used to prevent or manage corrosion in various industries.

1.2 Types of Corrosion

Corrosion manifests in various forms each influenced by specific environmental conditions, material properties, and the nature of exposure [6]. Understanding the different types of corrosion is essential for diagnosing problems and implementing effective prevention or mitigation strategies [3, 7]. An illustrative representation of these corrosion types is provided in Figure 1.1. Below are the most common types of corrosion:

1.2.1 Uniform Corrosion

Uniform corrosion, also known as general corrosion, is the most common form and occurs evenly across the entire surface of a material. This type of corrosion is predictable, as the material gradually deteriorates at a consistent rate when exposed to corrosive environments, such as air, water, or chemicals. Uniform corrosion typically leads to thinning of the material, which can be counteracted through coatings, inhibitors, or material selection. Despite its widespread occurrence, uniform corrosion is often easier to manage because its rate can be accurately estimated [9].

1.2.2 Pitting Corrosion

Pitting corrosion is a localized form of corrosion that results in the formation of small holes or pits on the material's surface. These pits can be difficult to detect initially, but they can lead to significant damage over time, especially in stainless steel and other passive metals. Pitting often occurs in environments containing chloride ions, such as seawater, and can quickly penetrate a material leading to structural failure. Even though the overall loss of material may be minimal, the concentrated nature of pitting makes it particularly dangerous [10]. Figure 1.2 illustrates a pit in stainless steel.

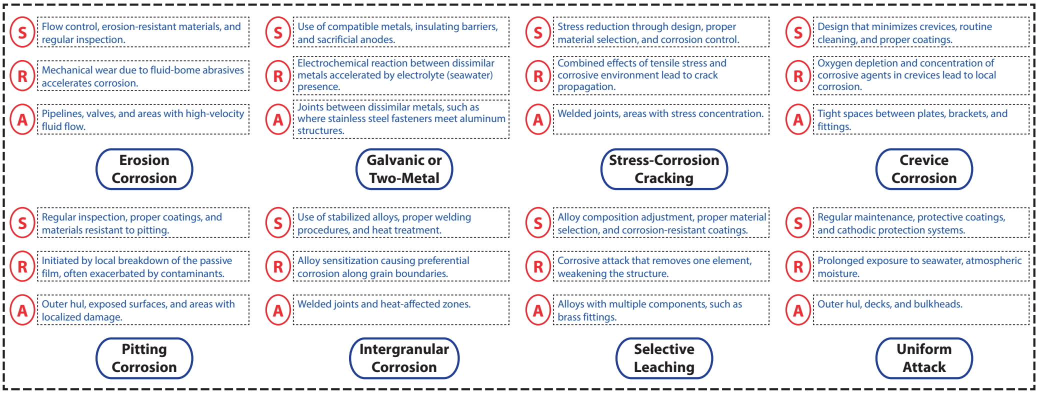

Figure 1.1 Eight different types of corrosion, where A, R, and S represent the area mostly affected, the reason for particular corrosion, and the solution, which can prevent or reduce the rate of corrosion, respectively [8].

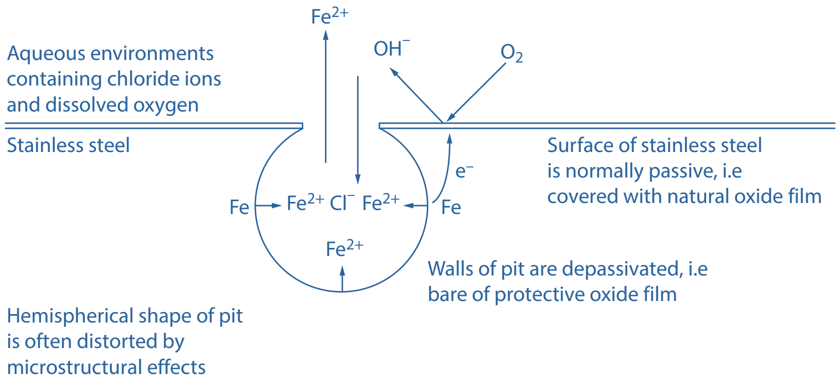

Figure 1.2 Pitting corrosion of stainless steel.

1.2.3 Crevice Corrosion

Crevice corrosion (Figure 1.3) occurs in areas where a stagnant solution is trapped within narrow spaces, such as joints, gaps, or under seals. These confined spaces can create micro-environments that promote corrosion due to a lack of oxygen or the accumulation of corrosive substances. Like pitting, crevice corrosion is often found in chloride-rich environments and can lead to rapid material failure if not properly addressed [11].

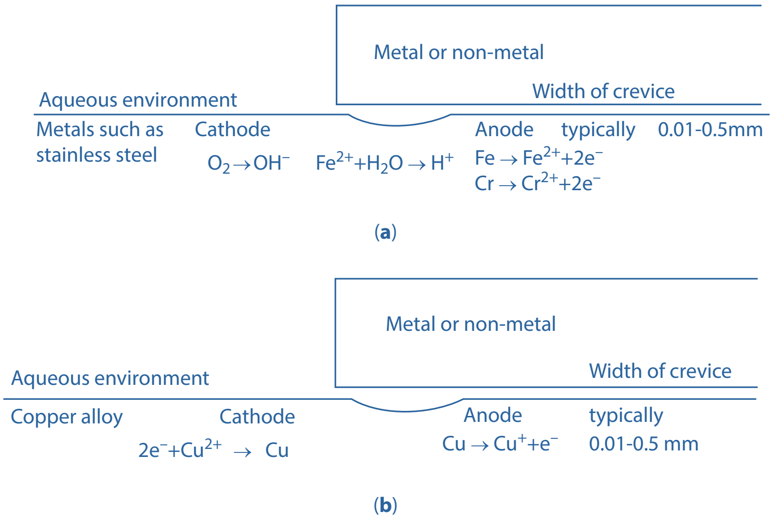

Figure 1.3 Crevice corrosion driven by (a) a differential aeration cell and (b) a differential metal ion concentration cell [2].

1.2.4 Galvanic Corrosion

Galvanic corrosion arises when two dissimilar metals are in electrical contact with each other in the presence of an electrolyte, such as water. The more reactive metal, known as the anode, corrodes faster, while the less reactive metal, the cathode, is protected. Galvanic corrosion is a common issue in marine environments or systems where multiple metals are used together. Figure 1.4 depicts a metal, such as iron, steel, or zinc, immersed in electrolyte such as sodium chloride solution. Preventive measures include the use of insulating materials, coatings, or selecting metals with similar electrochemical potentials.

1.2.5 Intergranular Corrosion

Intergranular corrosion affects the grain boundaries of a metal. This type of corrosion is especially problematic in stainless steels that have been improperly heat treated or welded. The grain boundaries become susceptible to attack, while the bulk of the material remains unaffected leading to a weakening of the structure and eventual failure. Proper material selection, heat treatments, and alloying can help mitigate intergranular corrosion [12].

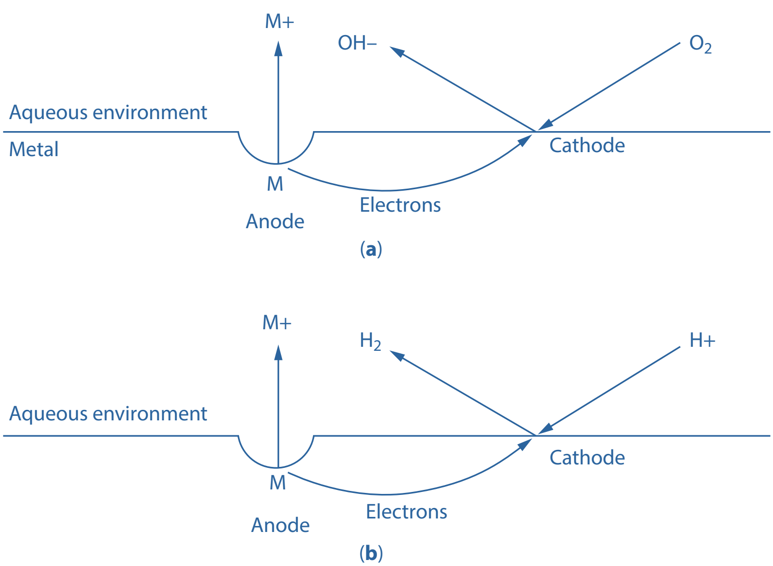

Figure 1.4 Anodic and cathodic corrosion reaction [2].

1.2.6 Stress Corrosion Cracking (SCC)

Stress corrosion cracking occurs when a material is subjected to tensile stress in a corrosive environment. The combination of mechanical stress and corrosion leads to the formation of cracks, which propagate over time and may cause sudden and catastrophic failure. SCC is particularly dangerous because it can occur without obvious signs of corrosion. It is commonly found in pipelines, aircraft, and industrial equipment. Controlling stress levels, using corrosion inhibitors, and selecting resistant materials are key strategies to prevent SCC [13].

1.2.7 Erosion Corrosion

Erosion corrosion results from the combined action of mechanical wear and chemical attack. This type of corrosion is common in environments where fluids are moving rapidly, such as in pipes, pumps, and turbine blades. The constant flow of abrasive particles or fluids removes protective films or coatings from the surface exposing the material to accelerated corrosion. Reducing flow velocity, using erosion-resistant materials, and applying protective coatings can help mitigate this form of corrosion [14].

1.2.8 Corrosion Fatigue

Corrosion fatigue occurs when a material is subjected to cyclic loading in a corrosive environment. The repetitive mechanical stress, combined with the corrosive attack, weakens the material over time and leads to the initiation and growth of fatigue cracks. This type of corrosion is a significant concern in industries, such as aerospace, automotive, and marine, where materials experience both stress and exposure to corrosive elements. Proper design, material selection, and protective coatings are essential for reducing corrosion fatigue [15].

1.2.9 Microbiologically Influenced Corrosion (MIC)

Microbiologically influenced corrosion (MIC) is caused by the activity of microorganisms, such as bacteria, fungi, or algae, which can either directly or indirectly accelerate corrosion processes. MIC is often found in pipelines, water systems, and offshore structures where biofilms form on material surfaces. Sulfate-reducing bacteria (SRB) are one of the most common culprits, producing hydrogen sulfide, which can lead to the rapid

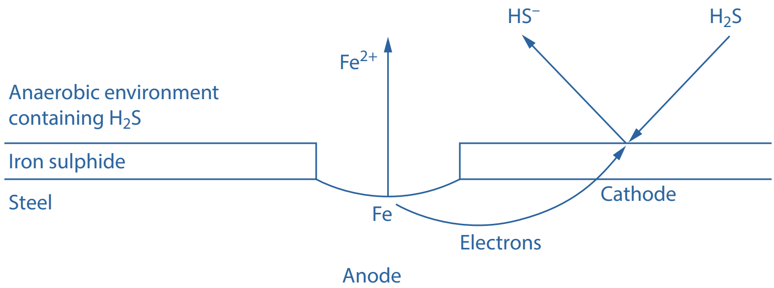

Figure 1.5 Microbially influenced corrosion [2].

deterioration of metals (Figure 1.5). Regular cleaning, chemical treatments, and the use of biocides are common preventive measures against MIC [16].

1.2.10 Hydrogen Embrittlement

Hydrogen embrittlement occurs when hydrogen atoms diffuse into a metal leading to a significant reduction in ductility and toughness. This makes the metal brittle and susceptible to cracking under stress. Hydrogen embrittlement is particularly problematic in high-strength steels and alloys often occurring in environments where hydrogen is present such as during corrosion or electrochemical processes like plating. Preventive strategies include reducing hydrogen exposure, heat treatments, and the use of resistant materials [7].

1.3 Corrosive Environments

Corrosion is intrinsically linked to the environment in which materials exist. Every environment, to varying degrees, exhibits corrosive potential affecting materials based on the surrounding physical and chemical conditions. Understanding the specific environmental factors contributing to corrosion is essential for devising effective mitigation strategies [17]. The following are some common types of corrosive environments:

i. **Air and Humidity:** Atmospheric conditions, particularly those with high humidity, promote oxidation and other corrosion reactions, especially in metals like iron.
ii. **Fresh, Distilled, Salt, and Marine Water:** Water in all its forms—freshwater, distilled water, and especially

saltwater—can act as a corrosive agent. Marine environments are particularly harsh due to the presence of chloride ions, which accelerate corrosion.

iii. **Natural, Urban, Marine, and Industrial Atmospheres:** Different atmospheric conditions, such as rural, urban, and industrial settings, pose various corrosion risks. Urban and industrial atmospheres contain pollutants, like sulfur dioxide and nitrogen oxides, which increase the corrosivity.

iv. **Steam and Gases (e.g., Chlorine):** High-temperature steam and reactive gases, such as chlorine, lead to accelerated oxidation and other forms of chemical degradation in exposed materials.

v. **Ammonia:** Ammonia-containing environments can cause stress corrosion cracking and other forms of localized attack, particularly on copper and its alloys.

vi. **Hydrogen Sulfide:** Common in industrial settings, like oil and gas production, hydrogen sulfide is highly corrosive, especially to metals, like steel, leading to sulfide stress cracking.

vii. **Sulfur Dioxide and Nitrogen Oxides:** These industrial pollutants contribute to acid rain formation, which significantly increases the rate of corrosion in metals, concrete, and other materials.

viii. **Fuel Gases:** Gases resulting from combustion processes, such as carbon monoxide or hydrocarbons, can create corrosive deposits on metal surfaces and corrode pipelines and infrastructure.

ix. **Acids:** Acidic environments, such as those containing sulfuric or hydrochloric acid, are among the most aggressive corrosive environments rapidly attacking metals and causing severe material loss.

x. **Alkalies:** Strong alkaline environments can cause corrosion in specific metals, such as aluminum and zinc leading to surface degradation and failure.

xi. **Soils:** Soil corrosion is influenced by factors such as moisture content, acidity, and the presence of salts. Underground pipelines and structures are particularly vulnerable to soil corrosion.

These corrosive environments demonstrate that corrosion is a significant force that depletes resources, impacts the economy, and causes untimely failures in infrastructure, machinery, and components. Addressing these challenges requires careful environmental assessment and appropriate corrosion prevention techniques.

1.4 Consequences of Corrosion

The recognition of corrosion as a significant problem dates to the 1960s when it became evident that its impact extended far beyond material degradation—it was affecting the economies of developed nations, shortening the useful life of manufactured goods, and wasting valuable resources through anti-metallurgical processes. Corrosion's implications go beyond financial losses; it also poses risks to human life, compromises safety, and causes extensive environmental damage.

Each year on April 24, Corrosion Awareness Day brings attention to the substantial global costs associated with corrosion. The economic toll and environmental impact have been the driving forces behind much of the current research into corrosion prevention and control. Several nations have undertaken corrosion cost studies to assess its economic effects leading to valuable insights that have shaped corrosion management strategies.

In one of the earliest reports on corrosion costs, published by Uhlig in 1949 [18], the annual cost of corrosion in the United States was estimated to be 2.1% of the Gross National Product (GNP). By the mid-1970s, the situation had worsened, with studies estimating that in 1975, the total loss due to corrosion in the U.S. amounted to $70 billion, approximately 5% of the GNP. These staggering figures prompted more detailed investigations [19].

A landmark study conducted in 2002 by the U.S. Federal Highway Administration (FHWA), in collaboration with the National Association of Corrosion Engineers (NACE) International, calculated the direct cost of metallic corrosion in U.S. industries to be $276 billion annually, or approximately 3.1% of the country's GNP [20]. Notably, this figure included only direct costs such as the replacement of corroded materials and equipment. Indirect costs, which can be just as substantial, include output losses, environmental damage, transportation disruptions, and accidents. These indirect costs are often estimated to match or even exceed direct corrosion-related expenses.

Other countries have conducted similar studies, with nations, like the UK, Japan, Australia, Kuwait, Germany, Finland, Sweden, India, and

China, all assessing their respective economic losses due to corrosion. The results have been consistent, with the annual cost of corrosion generally falling between 1% and 5% of each country's GNP. Global economic losses due to corrosion were estimated by NACE International in 2016 to be a staggering $2.5 trillion. In India, for example, a 1984–1985 study calculated the direct cost of corrosion to be Rs. 40.76 billion, with Rs. 18.04 billion deemed avoidable. A later report in 1997 estimated India's annual corrosion losses at Rs. 250 billion or 4% of the GNP. The latest global studies by NACE indicate that corrosion costs India 4.2% of its GDP [21].

Figure 1.6 presents a comparison of corrosion cost associated with different countries GDP.

Beyond the economic consequences, corrosion has led to multiple structural failures that pose serious risks to human health and safety, as well as to the environment. Catastrophic failures of infrastructure, pipelines, bridges, and other critical systems have been linked to corrosion causing accidents, injuries, and even fatalities. The safety and environmental costs associated with corrosion are difficult to quantify, as the consequences often extend beyond immediate financial losses. Corrosion-related environmental damage, such as leaks from pipelines and containment failures, can result in long-lasting contamination of ecosystems [3].

For these reasons, corrosion control is not merely a matter of economic efficiency but also a critical concern for public safety and environmental preservation. Effective corrosion management can minimize accidents, conserve materials, and reduce environmental pollution, thereby providing broader benefits to society.

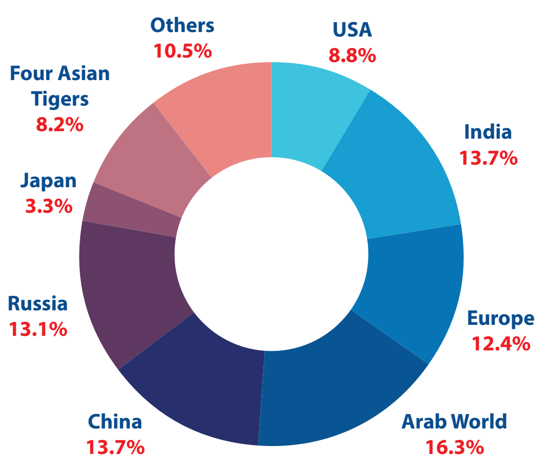

Figure 1.6 Corrosion cost associated with countries GDP [8].

1.5 Corrosion Monitoring in Industrial Environments

Once a plant is operational, it becomes essential to monitor the progress of corrosion to prevent potential failures and optimize maintenance efforts. Effective corrosion monitoring helps to mitigate risks, enhance plant safety, and improve overall economic performance. Monitoring techniques vary in sophistication, cost, and suitability based on the plant's design, the anticipated corrosion mechanisms, and the potential impact of failure. Key areas of the plant that are more prone to corrosion or where catastrophic failure could occur require closer monitoring. Corrosion monitoring also plays a crucial role in avoiding overdesign enabling the use of cost-effective materials while ensuring operational safety [22]. Below are the primary methods of corrosion monitoring:

1.5.1 Physical Examination

The simplest and most traditional method of monitoring corrosion is through regular physical inspections. Detailed records of all construction materials used in the plant must be maintained and updated when repairs are performed. Visual inspections of both external and internal surfaces during scheduled shutdowns can identify most corrosion effects, such as leaks or cracks, providing early warnings before catastrophic failures occur. In addition to visual inspection, several non-destructive testing (NDT) techniques can be employed to detect and quantify corrosion:

A) **Ultrasonic Testing:** Measures wall thickness to monitor general corrosion, detect cracks, and identify hydrogen blisters. Suitable for *in situ* examination, except at temperatures above 80°C.

B) **Magnetic Particle Inspection:** Detects surface and sub-surface cracks in ferromagnetic materials.

C) **Dye Penetrant Testing:** A simple method requiring minimal operator training, useful for identifying fine cracks such as those caused by chloride stress corrosion in stainless steels.

1.5.2 Exposure Coupons and Electrical Resistance Probes

Exposure coupons and electrical resistance probes offer a way to assess corrosion behavior under specific operating conditions, especially when process changes occur or materials are being evaluated for replacement.

a) Exposure Coupons: Small metal samples (coupons) are suspended in the process stream and periodically removed for analysis, such as weight loss determination or visual inspection for localized corrosion. These provide an integrated corrosion rate over the exposure period.
b) Electrical Resistance Probes: Strands of material are inserted into the process stream, and their electrical resistance is monitored over time. The probe's resistance increases as its cross-sectional area decreases due to corrosion providing real-time data on corrosion rates. However, these techniques primarily give information on general corrosion and are less effective in detecting localized forms like pitting or crevice corrosion.
c) Electrochemical Corrosion Monitoring: Electrochemical methods provide a more immediate measure of corrosion rates and can be particularly useful in dynamic environments where corrosion rates fluctuate with changing process conditions. These techniques include the following:

***Polarization Resistance*:** Measures the current-potential behavior of a metal when polarized around its corrosion potential. This method provides an instantaneous indication of the corrosion rate, often used in real-time monitoring.
***Impedance Spectroscopy*:** An advanced method extending polarization resistance into low-conductivity environments, including atmospheric corrosion and thin liquid films. It also provides insights into the mechanisms of corrosion.
***Electrochemical Noise*:** Monitors the electrical noise on the corrosion potential of a metal without external polarization. This technique can detect localized corrosion forms such as pit initiation and stress corrosion cracking.

1.5.3 Thin-Layer Activation

A more specialized technique, thin-layer activation, involves creating a radioactive layer on the surface of the plant's equipment. As corrosion occurs, radioactive isotopes of the construction material dissolve into the process stream, and their detection allows for quantification of the corrosion rate. Although not yet widely used, it has shown promise in several industries for providing localized corrosion rate data. By utilizing these various monitoring techniques, plant operators can gain a comprehensive understanding of the corrosion processes occurring in their systems. Monitoring enables timely intervention to prevent severe damage, enhance safety, and optimize the economic performance of the plant through reduced downtime and maintenance costs.

1.6 Conclusion

Corrosion is an inevitable and multifaceted process that affects a wide range of materials and industries, with significant economic, environmental, and safety repercussions. While advancements in corrosion science have deepened our understanding and provided tools to mitigate its effects, ongoing research and innovation are necessary to address the remaining challenges. Effective corrosion management requires a combination of material selection, environmental control, and advanced monitoring techniques. By applying these strategies, industries cannot only reduce the financial burden of corrosion but also enhance safety, prolong the lifespan of critical infrastructure, and mitigate environmental damage. As corrosion continues to pose challenges, particularly in high-risk environments, a comprehensive approach is crucial to ensure the sustainability and integrity of modern technological systems.

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