الجمهورية الجزائرية الديمقراطية الشعبة
REPUBLIQUE ALGERIENNE DEMOCRATIQUE POPULAIRE
وزارة التعليم العالي والبحث العلمي
MINISTERE DE L'ENSEIGNEMENT SUPERIEUR ET DE LA RECHERCHE SCIENTIFIQUE

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Course support

Specialty: Chemistry

Option: **ELECTROCHEMISTRY AND CORROSION**

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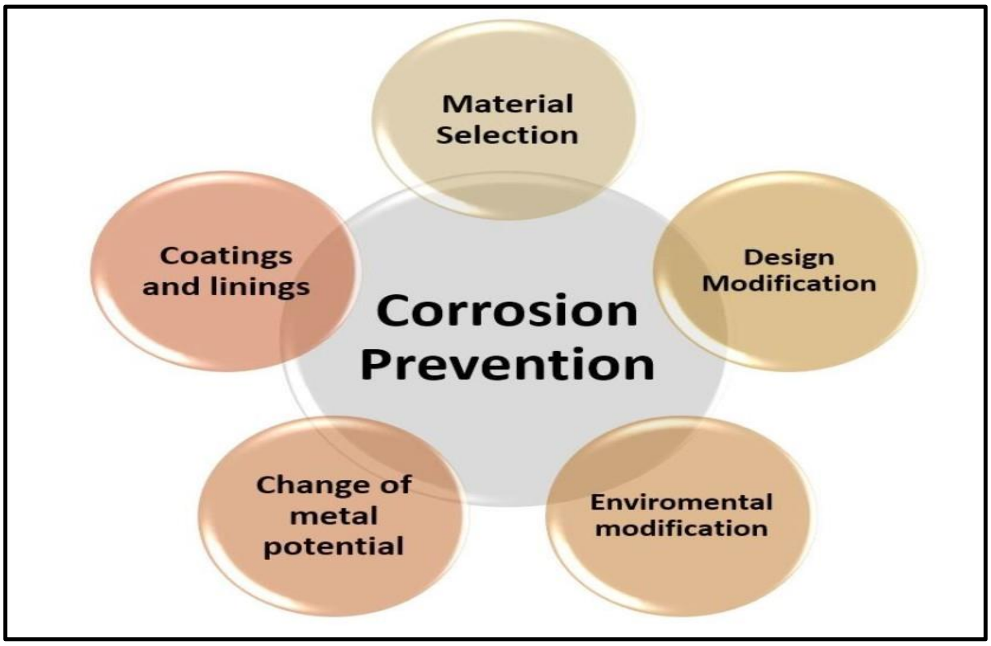
Entitled:

CORROSION PROTECTION AND CONTROL TECHNIQUES



2024-2025

Preface

History of metals and it has been looked on as a menace which destroys metals and structures and turns beauty into a beast. Our human civilization cannot exist without metals and yet corrosion is their Achilles heel. Although familiarity with corrosion is ancient, it has been taken very pas sively by scientists and engineers in the past. Surprisingly, it is only during the last six decades that corrosion science has gradually evolved to a well-defined discipline. Corrosion Science and Engineering is now an integral part of engineering curriculum in leading universities throughout the world. With the rapid advances in mate rials in the new millennium, the demand for corrosion engineering courses has dramatically increased. This has necessitated the need for the publication of new books. Professor U. R. Evans, Prof. H. H. Uhlig and Prof. M. Fontana wrote a classical generation of basic textbooks covering the fundamentals of corrosion science and engineering. These books served as texts for decades and some of the mare still being used. Several new books in corrosion have been published in recent years tocaterto the needs science and engineering students. As a teacher of corrosion engineering for the last twenty-five years, I found the material to be deficient in corrosion engineering content. However, sufficient coverage was given to the understanding of corrosion science and engineering.

Intitulé du Master : Electrochimie - Corrosion
Semestre *: 3*
Intitulé de l'UE : UEF1(O/P)
Intitulé de la matière 1: Techniques de Protection et Contrôle de la Corrosion
Crédits : 4
Coefficients :3

Objectifs de l'enseignement

Acquérir des connaissances sur toutes les méthodes de protection des matériaux métalliques
Application des méthodes de lutte contre la corrosion aux ouvrages de transport
Prévention de la corrosion dans le cas des ouvrages de transport
Etude et planification des travaux de protection

Connaissances préalables recommandées :

Avoir suivi les cours de corrosion et d'électrochimie.

Contenu de la matière :

1-Méthodes de prévention contre la corrosion
2- Conception des ouvrages (design)
3- Choix des matériaux (sélection des matériaux)
4-Action sur l'environnement
5-Inhibiteurs de corrosion
6-Protection cathodique
7-Protection anodique
8-Revêtements organiques
9-Revêtements métalliques
10-Surveillance de la corrosion

Mode d'évaluation : Contrôle Continu (devoirs et interrogations écrites). Examen Final

Références

-Corrosion and Protection
Einar BARDAL., Springer 2003
-Protection Cathodique dans la lutte contre la corrosion.
Théorie et pratique., John. H. MORGAN., Dunod, Paris 1966.
-J.-L. Crolet et G.More , « politique et choix d'un revêtement, traitements de surface et protection contre la corrosion. Les éditions de physique , Paris 1989.
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Théorie et pratique., John. H. MORGAN., Dunod, Paris 1966.

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CHAPTER I

CORROSION PREVENTION METHODS

Chapter I : Corrosion prevention methods

I.1. Introduction to Corrosion

Most structural and engineering materials in use today are metals, which are subject to corrosion due to their thermodynamic instability with respect to the environment. Where corrosion exists in an index of the extent of corrosion damage, the commonest method until recent times employed by engineering designers has been to apply self-supporting coatings to metals which shield the protective oxide film from interference and add both chemical and ferrous protection against attack. Corrosion, the deterioration of a substance used in production, processing, and fabrication, is relevant to every facet of human existence. A broader definition describes corrosion as the detrimental effects of submerged and atmospheric waters, dirt, grease, man-made organic and inorganic substances on processes, machines, materials, structures, and fittings used in agriculture (Oki and Anawe, 2015). Metals are vulnerable to corrosion from many chemicals. A liquid phase containing other materials mixes with water to cause rapid deterioration of metals by corrosive agents. In the first ten years of cultivation in a particular environment, corrosion products protect the metal against further attacks. Most damage occurs in underground installations buried with solutions containing corrosive agents.

Protection against corrosion is a process where infrastructure materials are shielded from premature deterioration. Costs to combat corrosion are high, yet engineering assessments and designs are reliable and considerable effort is expended to ensure successful applications over prolonged periods. For a maintenance manual to efficiently cover visible corrosion, it is not easy to compile lists of structures, machines, and fittings that could be most damaging if corrosion were to occur in them. Each is an independent work that requires experts to assess and evaluate each installation without neglect of attention to detail. Because of the capital-intensive nation, agriculture and horticulture takes practice over time, using expert opinion is the best method. However, this opinion is subjective without true evaluations.

I.2. Corrosion Prevention Techniques

Corrosion problems impact capital- and maintenance-intensive structures such as pipelines, oil storage tanks, offshore structures, and transportation fleets. Selection of appropriate and cost-effective corrosion protection methods is crucial, but difficult because the cost and effectiveness of corrosion protection methods depend upon structure and environment. Generally, all kinds of corrosion problems follow similar corrosion and prevention mechanisms. If there are metals, electrolytes, and electrochemical contact between them, corrosion will occur. In a simple electrochemical corrosion cell, there are anode and cathode. Anode (corroded areas, producing electrons) and cathode (sites for electron-consuming reaction) must be at different locations on the metal surface. Metals and electrolytes are substrates and reactants respectively. Reducing the rate of electrons released from anode can mitigate the corrosion problem. The prevention of the electrochemical contact between metal and electrolytes is also useful. Then, both concepts can bring about three common corrosion protection methods: (1) Barrier Coating: thin-film coating, painting, or inhibitor can be applied as the barrier layer. This method is often applied on the anodic substrate such as carbon steel. Maintenance activities after coating or painting are needed to maintain the effectiveness. (2) Material selection: selection of appropriate materials is crucial because it involves anti-corrosion and financial concern. High corrosion resistant material is normally expensive but provides a longer lifetime. (3) Cathodic protection: an electrochemical technique used to control corrosion making it the cathode of an existing corrosion cell. The metallic equipment can be protected by connecting it with sacrificial metals acting as the anode. A periodic replenishment becomes necessary. The impressed current can also change the metallic equipment to be a cathode material. Routine monitoring is also important to check the status of the impressed current system.

I.2.1. Protective coatings

An effective means of limiting corrosion is provided by organic coatings (Roy Orgon, 2015). Coatings serve as a physical barrier between the metal substrate and exposure environment. No coating will form a perfect barrier to corrosive environments as water, oxygen, and ions are all capable of penetrating organic films. Underfilm corrosion begins when the electrolyte has penetrated to the metal surface, and cathodic and anodic reactions are initiated. Low pH conditions develop at the anodic sites, attracting chloride ions and creating a cell prone to pitting corrosion. At the cathodic locations, the environment becomes highly basic, causing the coating to delaminate from the substrate (Ammar et al., 2018). Overall barrier performance is influenced by several factors, including mass transfer and exposure environment coating thickness, coating network properties, coating-metal adhesion, and chemical degradation of the coating over time. Coatings can be considered composite materials, as many coatings are based on combinations of pigments and a polymer resin. Before application, the uncured coating is suspended in solvent. The main functions of the solvent are means of material transfer, modifying viscosity for proper application, and an aid in film formation and leveling. Once a uniform film is formed, the solventborne coatings rely on the timely evaporation of the solvent, allowing the film to coalesce and cure by desired mechanisms.

Polymer and polymeric-based coatings have been investigated as this will improve the performance of the coating against environmental attacks. In addition to the excellent protective performance, many polymers exhibit fairly good mechanical, thermal, and optical properties which are important for practical applications. It has also been shown that the protection performance of polymeric materials could be improved by the incorporation of nanoparticles within the polymer matrix or by polymer entrapment on ceramic nanoparticles. A potential solution to these requirements would be the incorporation of chemically stable ceramic particles within an organic polymeric matrix. The versatility of both ceramic and organic materials in terms of their reactivity and availability, as well as their processing methodology could be beneficial towards achieving the desired performance.

I.2.2. Cathodic protection

A cathodic protection (CP) system is composed of a power supply, anodes, and a stub to obtain the protection potential at the structure. There are basically two types of CP: the impressed current type and the galvanic anodes type, being the impressed current the most widely used due to its benefits.

An impressed current cathodic protection system uses a rectifier to convert alternating current to direct current for usage. The conversion from AC to DC is carried out through diodes, and later the current can be controlled outputting voltages and currents. Due to the CP structural configuration, the cement concrete is almost a dielectric barrier. A correct CP design must consider this geometry, leading to a highly non-linear propagation of the electric fields along the protected pipeline. As the structure is at most electrically conductive, it will not behave as a dipole when influenced by the electric field, but the propagation of the fields resembles a strongly attenuated bipolar pulse. This means that far from the points anodes the potential will be more negative due to the protection, but this observation cannot be taken as a proportion of its magnitude reduction.

Impressed current cathodic protection is applied to mitigate corrosion on reinforced concrete structures with corroded steel reinforcement. In this system, a DC source causes current flow which minimizes corrosion potential. A structure receives an ICCP system installed with a graphite band as auxiliary anode around the ground. Provided with a rectifier, monitoring devices were connected to the ICCP system to monitor and regulate the potential on the steel surface through the control of the applied current. Successful indications were achieved through the completion of monitoring periods with average density imposed. Involvement of embedded steel bars and grounding connection cause difficulties in monitoring activities. Therefore, it was decided to develop a simple and efficient model that summarizes monitoring measurements into one whole and applicable figure. A feasible alternative was suggested with current density accumulation approach. Total steel area current density in the ICCP system of reinforced concrete bridge was calculated by digitizing the area surrounding the ground.

I.2.3. Anodic protection

This system is usually applied to metals with decentralized structures that are reachable/accessible for a portable anode. An active anode is the core of the system: with immersed metals, an effective, constant current density of 0.3 A/m2 produces the formation of passivating oxide on metals' surface. For less noble metals, constant or variable anode surface with variable current density is applied. In the last case, initial = 2 or 3 times greater than passive, steady = ^2⁄3 * 1st one value. This can be achieved with programmed anodic potential through a DC generator through programmmanual or computer/embed control circuit. A portable unit consists of equipment: potential measuring equipment and a DC current source generator with constant or programmable potential as well as time controller. The system usually applies on metals with decentralized structures reached/accessed for portable anodes close to metals in water medium (M. (E) Noamy et al., 2016). For metals usually Cathodic Protection System is applied for metals with anode much greater than the inspected surface. For selected close to metals anodes constant/variable anode voltage is applied and inspected metal steel or grate is combined in CE with potential measuring unit. Automated systems consist of programmed DC current source with potential measuring unit.

Pros: Effective restoration of metals' passivation when operating in Cl- medium. Easy construction, operation, and programming. For short-time operation it is possible for relatively cheap passive metals applying programming systems, effective and performing PC, which doesn’t destroy metal's surface and geometry. Simple problem construction. Effectivity on different metals surfaces restoration by different neat models of State of the Art anodic protectors.

I.2.4. Material selection

The most effective and cost-efficient method of preventing corrosion in workpieces manufactured or to be manufactured is the proper choice of materials. If the corrosion resistance of materials is known, in addition to their mechanical properties, processability, and availability, this is often more advantageous than further treats. The materials come into contact with different media and fluids in the operation of machinery, which cause various corrosion types and corrosion mechanisms. If a machine component is manufactured from the most suitable material, the implementation and costs of possible post-treats can be avoided. Many metals and alloys have been internationally standardized due to their industrial importance, and their corrosion behaviour, such as hardenable alloys, stainless steels, weatherproof alloys, and austenitic and ferritic steels, is part of the standard assessment of corrosion protection (Hagarová et al., 2021). However, selection cannot be exactly automatic since many factors influence the corrosion mechanism such as media temperature, nozzles, stray currents, etc. For example, usually, cast iron is selected for a coolant flux area, but its corrosion resistance is questionable due to media turbulence as it is a component of an automobile engine (Victal do Nascimento et al., 2019).

The material recommendation analysis of machine components and reasons for recommendation change was carried out. Each corrosion type and mechanism were introduced. The sorting of material classes and its metallography were also outlined, followed by its common applications. Recognized surface treatment types were also highlighted. The corrosion behaviour and maintenance of recommendable materials were also assessed. Additional recommendations on the material or surface treatment type can be made on the material recommendation assessment, and corrosion preventive posts for given applications were also described. The methodologies were illustrated in charts and diagrams with engineering design aspects. A case study of 28 machine components of an ocean drone's components and a case study of European and Asian company's weapon turret components were detailed to show the Mason methods as an analysis method and a corrosion type detection procedure.

I.2.5. Corrosion inhibitors

Corrosion is a serious problem in many industries. Corrosion occurs when metals are in contact with a corrosive environment, resulting in damage and wastage. It is essential to control this menace in order to ensure the proper functioning and productivity of machines. Corrosion-induced failures in machinery parts make up 10% to 30% of daily breakdowns. These failures are caused by unfit materials, poor handling, bad practices, corrosive environmental conditions (chemical and microbiological), and poor maintenance. Corrosion cannot be completely eliminated; it can only be controlled. Prevention methods must be adopted, which can be grouped into five categories: galvanic protection, protective coatings, corrosion inhibitors, corrosion monitoring, and good practices.

Corrosion inhibitors are chemicals that, when added in small amounts to the corrosive environment, will reduce corrosion rates. Inhibitors can be classified as anodic, cathodic, mixed type, volatile, or non-volatile. There are many green inhibitors, but very few are used in practice. In the petroleum industry, these inhibitors are used mainly because of their vapor phase inhibition capabilities on buried pipelines. An efficient corrosion inhibitor slows down the anodic or cathodic reaction and reduces the corrosion current. The anions in an electrolytic solution create passivating films on electrodes. Nitrobenzenes, aromatic carboxylic acids, and phosphonic acids can inhibit corrosion through film formation on the metal surface. The protective coating slows down the electrochemical processes and slows down corrosion. Adsorption that effectively slowed acid corrosion was made possible by the inhibitor's contact with the steel surface using its nitrogen and oxygen atoms (Khamees Thabet et al., 2023). Coatings are developed to offer protection against corrosion. Pastes, rubber, and electrodeposited paints are some of the covers used. The mishandling of these covers rendering them ineffective must be controlled.

The use of corrosion inhibitors is a widely accepted method for controlling corrosion. Organic compounds are frequently used as corrosion inhibitors. These compounds are environmentally safe and provide effective protection against corrosion at low concentrations. It has been established that the performance of the adsorbed layer depends on the surfactant concentration and the time of contact with the metal surface (Oki and Anawe, 2015). Stickers, phosphates, oxalates, and mercaptans are used as coatings on machinery, but these coatings reduce the aesthetic qualities and are not generally of a permanent type.

I.2.6. Environmental control

Atmospheric corrosion is familiar in the corrosion of unprotected metals surfaces such as steel structures, steel reinforcement in concrete whilst the construction of bridges, highways, buildings, storage tanks, pipelines, offshore oil rig platforms, and other infrastructure. Several piles of theoretical and experimental evidence confirm that atmospheric corrosion is caused by the influence of moisture vapour in the ambient atmosphere. Perhaps the most important factor in atmospheric corrosion is moisture itself, either in the form of high relative humidity and/or as condensate on the surface of a metal substrate (Nazir et al., 2018). The maximum amount of moisture that the atmosphere can hold increases as the temperature increases. When the atmospheric temperature decreases or dew point rises and/or during the night when the relative humidity increases, all the atmospheric moisture cannot be retained by the atmosphere leading to condensation forming a thin electrolytic film layers on the surface of steel and other metals. This thin layer along with pre-existing corrosive contaminants deposits on the surface of steel such as hygroscopic salts forming a high alkaline electrolytic solution which accelerates the corrosion rate. While this thin film on metal surface is almost invisible, the corrosive contaminants it contains are known to reach relatively high concentration, especially under the operating conditions of structures in outdoor open atmosphere and places near coastal regions.

Corrosion does not only occur in confined pools of solution where the electrochemical processes are well understood but occurs also in a thin film of solution spread on the metal surface across which the solid supports either side of the humid air gap through which oxygen diffuses to the corroding site. Common to studies of the conditions of condensation is the discovery of what has come to be known as the critical relative humidity, a relative humidity at which the otherwise dry surface becomes vulnerable to atmospheric corrosion by becoming wetted (Leung et al., 1980). Although the concept of critical relative humidity is widely accepted and applied as a basis for corrosion prevention and design consideration, there is still no reliable general theory of the dependence of critical relative humidity on natural factors. The most serious difficulty of a general theory of critical relative humidity is the problem of getting at the boundaries of an appropriate system in which to carry out a modelling study commensurate with the many body nature of atmospheric gases and surface adsorbates. The investigation permits a chemical surface lattice simulation of metal corrosion to be applied on the lowest par formation and destruction to be achieved in the vapour case without the aid of mechanical trapping.

I.3. Protective coatings

An important means of limiting corrosion of metals is the use of organic coatings. A coating or paint serves as a physical barrier between the metal substrate and exposure environment. No coating will form a perfect barrier to corrosive environments and water, oxygen, and ions can penetrate organic films. Degradation of coating performance begins with water and oxygen penetration into the film. Underfilm corrosion begins when the electrolyte has penetrated to the metal surface and the coating is said to be breached. At this point, cathodic and anodic reactions are initiated at the metal surface. No metal is absolutely passive and in the presence of an electrolyte, the surface of the metal will be in a state of change, undergoing oxidation and chemical attack. As a consequence, corrosion products accumulate at the surface and provide a barrier layer to the underlying metal. For aluminum metal there is a naturally passivating oxide layer formed during branching of the metal into its elemental state. Aluminum metal is highly active in terms of corrosion; however, corrosion of aluminum is restricted by the formation of a thick layer of a passive oxide film at the metal surface. Specific ions in the electrolyte, usually Cl-, can cause a localized breakdown in the passive layer, exposing a small area of the metal surface for rapid oxidation. This effect is amplified in alloyed metals, where precipitates of the alloying elements create surface abnormalities that are selectively attacked and subject to pitting. At these active pitting sites, metal dissolution is favored and Cl- ions are attracted to the charged surface, destroying the imposed control of the oxide layer. Low pH conditions develop at the anodic sites, accelerating the attacking reaction. The anodic reaction produces Al3+ cations and the setup of an electrochemical cell with elevated concentration of cations is detrimental to the durability of the underlying metal. An effective means of limiting this type of corrosion is provided by organic coatings, which serve as a physical barrier between the metal substrate and exposure environment (Ammar et al., 2018). Overall barrier performance is influenced by a number of factors including the exposure environment, the thickness and network properties of the coating, and adhesion between the film and substrate, as well as chemical degradation of the film over time and application. Coatings can be considered composite materials, based on various combinations of pigments and a polymer resin. Before application, the uncured coating is suspended in solvent. An important aspect of formulation is the selection of a solvent to modify the viscosity to allow for proper application of the coating, while at the same time assisting in film formation (Roy Orgon, 2015).

I.3.1. Types of coatings

Coatings can be used to inhibit corrosion, either alone or in conjunction with a cathodic protection technique. Most coatings used are organic in nature and give results of various quality depending on the environment in which they are exposed. Internally, coatings are applied on concrete to protect it against aggressive ions from water to improve durability and service life. Externally, coatings are applied on structural steel used for bridges and highway overpass applications, and on tanks used to store hazardous materials that can adversely affect the environment and surrounding property. To prevent corrosion, the coatings must adhere to the steel and also have durability against the environment. Wetness of the metal surface and the existence of oil are known to drastically compromise coating adhesion. Therefore, effort is digitized on establishing proper cleaning systems in order to prevent corrosion (Ammar et al., 2018).

Zero-bonus and pre-surface characterization of a new, inexpensive non-ground cleaning process is presented. This cleaning process is based on using aqueous surfactant solutions. It is shown that this cleaning procedure visibly removes most of the rust and oil from the surface of the steel substrate. Pre-coating tests suggested that it has coating acceptance comparable to grit-blasting and is a mechanism that generates a naturally-fine surface condition. The objectives of the study are to directly obtain and quantify, through advanced microscopic and spectroscopic measurements, the surface conditioning of the substrates by this new non-ground cleaning mechanism. The effectiveness of this process in preventing corrosion of steel in marine environment is also examined (Roy Orgon, 2015).

Aluminum metal is highly active in terms of corrosion. However, when in a pure form, aluminum can often restrict corrosion by the formation of a passive oxide film at the metal surface. Under wet conditions, this native oxide metastable in nature forms on contact with the environment, and within hours forms a stable oxide. Specific ions in the electrolyte, usually Cl-, can become adsorbed, catalyzing localized breakdown in the passive layer. Small areas of the metal surface are thereby exposed for rapid oxidation, which is fueled by the cathodic reduction of oxygen some distance away from the pit. This effect is necessarily amplified in alloyed metals, where precipitates of the alloying elements typically create surface abnormalities that are subject to pitting.

I.3.2. Application methods

In architecture, formations protected against corrosion have become well-known structures. Structures that require protection against corrosion usually have a constant plan form and air is free to circulate. If the structure is complex, inaccessible and involves cavities, prevention will be ineffective or performance expectancies will not be met. Protection requirements must be known to the designer from the beginning. Similarly, required tests and treatment methods must also be defined. These must all appear in the design drawings. Information on the electrolytic properties of structural materials and protection methods must also be included in the relevant specifications.

The last option is to coat areas to be protected against corrosion with protective coatings. Protective coatings can use a phenomenon that occurs in nature. Metal oxides almost always form a continuous layer on the surface of the material. This layer is based on the solubility of the oxide compound in the solution. If this solubility were infinite and there were no stimulus for oxide breakdown, protection would be complete. However, if it is disrupted, corrosion will begin. It is vital to know the kinetics of these processes, material passivability and the employed limitations. There would need to be strict conditions for coatings, including layer quality, porosity, density and structure if forces capable of disrupting nature's perfect construction were not used. The coating applied to the metal material must have a polarized potential below 0.3 V and an equivalent lime solubility of 1 mg/dm^3 if the metal is to remain passive. Equipment that interferes with these conditions must be protected beforehand (Gómez and Lana Villarreal, 2008).

I.3.3. Performance testing

The performance evaluation of corrosion protective coatings is important for reasonable engineering utilization. The evaluation of protective paint films on steel by x-ray diffraction techniques is significant.

Performance evaluations of organic coatings in corrosive environments are valuable for manufacturers and users of paints and coatings. EIS is a powerful tool to assess organic coatings for corrosion protection under laboratory conditions. An experimental setup and a methodology to assess protective coatings were developed. The novelty of the issue is that after coating degradation (most visible as a discoloration of the coating), EIS tests are conducted in distilled water at a limited range of frequencies and without any added electrolyte. EIS models, however, need to be simple and have fewer parameters to provide an interpretation of the widespread corrosion phenomena associated with the thin organic coating. Liquid media influence the EIS measurements of coating-covered metals even at the bulk resistance to cosmetic lacquer; diverse EIS models are available for uncoated metals.

Further studies can be expected to consider interference from lacquer degradation. The impedance tests were made in sintered glass cells by a potentiostat within a specified range. The signals which were not needed were cut off with a programmable timer. The coating was ruptured in the center of the upper glass cell. The detection limit was about 0.10 M NaCl concentration at a lower value of 10 g/l NaCl. Coating penetrations induce localized pitting corrosion on the metals which renewed vigorously at every exposure of rains and clearing efforts, ensured long soak of metals in saline for few hours and also of their coat/device as a damage testing unit after they were inspected for pitting sizes and number.

I.4. Cathodic protection

Different methods can be used for limiting corrosion, which can be broadly classified as galvanic control and impressed current control. In galvanic systems, an anode-cathode combination is formed such that the metal to be protected becomes the cathode and receives current from a suitable anode. Because different metals have more or less negative potentials, the largest potential drop occurs at the metal surface. DC power supply of suitable power capacity provides the necessary current to the anode. The impressed current can be directed into the buried pipeline using a suitable conductor. Similarly suitable protection anode will be placed either inside pipe or outside in the soil near the pipeline. Galvanic control has a limited life because eventually the anode is consumed, or the potential difference became negligible. However, this limits time available for passive resting of steel. Other disadvantages stem from flow velocity conditions, especially when gas pipeline cathodic protection (CP) is used with a disturbed liquid environment. Moreover, stray current from the pipe to station enclosures and sections without CP can become serious and CP tests are then needed. The concrete structure foundations often preclude the use of galvanic systems.

Essential aspects of assessment test interpretation can remain poorly understood even after extended experience and current design techniques. Understanding of test equipment limitations and physical phenomena involved can significantly improve interpretation of test results. Also these ideas will assist in selecting the best test equipment for test objectives. Interpretation of the test results obtain measures of agreement between the predicted and test data which says nothing about how closely the predicted and actual currents are. Comparison could involve overall current balance calculations over relevant time frames, which would characterize the test conditions and model performance. A current balance could be achieved by comparing the net current entering and leaving a structure using current and voltage measurements of various types. Some of these have serious shortcomings that could negate benefit of additional information obtained.

Application of Cathodic Protection to steel in concrete structures requires that the designer understands how rectifies operate, their selection, control and metering, and testing of all aspects of CP design and operation. Understanding and questioning the principal operation aspects of equipment in request for specifications and performance contracting is vital to avoiding inefficient operating with ulterior inconvenience. Cathodic protection is an important part of practically any concrete structure investigation. This is especially important in construction environments that may impact effective corrosion control failures. In environment which encourages corrosion the steel is fortunate to have adequate protective potential even in cracked concrete (Carmona Calero et al., 2017).

I.4.1. Sacrificial anodes

Corrosion is an electrochemical reaction that results in the destruction of a material, usually metals such as iron and steel, due to an electrochemical reaction in the presence of electrolytes. The protection of metals against corrosion can be achieved by either altering the environment or altering the structures and members. Sacrificial anodes are concerned with the cathodic protection of structures, a method of corrosion prevention that makes use of sacrificial anodes and electrically bonded steels which results in the negative biasing of the metals subjected to protection. An anode is a part of an electric device which sustains an oxidation reaction and is a source of electrons.

Sacrificial anodes are more easily corroded metals or alloys connected as electrically conducing to cathodically protect other more precious metals. The sacrificial anodes are pushed into concrete to be in contact with steel before backfilling concrete. According to Faraday's law, when metals are in contact, electrons flow from the first metal to the other due to differences in electrochemical potentials. Formation of such galvanic cell causes the cathodic reduction reaction on one metal and the anodic oxidation reaction on the other.

The metal with higher potential than another in aqueous solution experiences the anodic reaction behavior which is referred to as corrosion. In contrast, the protection is afforded to the cathode in which the cathodic reaction takes place. In a metal-cement paste-encased steel couple, electrochemical reaction occurs between the metals and hydroxide ions return to the couple through the bulk of the paste so that there is no net loss of the hydroxide ions in the paste. The flow of electrons enhances the corrosion of the anode and protects the cathode against corrosion (Ali Abubaker Al Jafri, 2003). Hence, the sacrificial anodes should be noble to cathodically protected steels and be physically separated from the buried surface of the steels not to contact with the cement paste. The metals with noble potential take corrosion as a result of anodic oxidation reaction, while the steels take cathodic reaction and are cathodically protected (A. Loto and P. I. Popoola, 2011).

I.4.2. Impressed current systems

The corrosion of buried structures may be controlled by systems of galvanic anodes as well as by impressed current systems. The impressed current systems consist of inert anodes which, with no corrosion, have a long life. However, in practice, irregular current distribution and dynamic RL loads make it difficult to maintain the output voltage. It is, therefore, important that new types of anchoring devices for impressed current systems be developed which will prevent clogging or deformation of the electrodes. As an alternative, once-through systems and a pattern of vertical rods, as energy sources, should be evaluated.

Anodes for the impressed current cathodic protection of bilge-type tanks supply a direct current so that the design and performance of the current-supplying devices determine the service of the anodes (Oleiwi, 1970). The anodes are buried in damp concrete or in the soil, and thus a lot of problems arise, such as the clogging of the porous medium of the anodes by corrosive products which will increase also a contact resistance and make the output voltage unstable, and the deformation of the electrodes or the anchoring devices which will prevent current distribution. These anodes are, therefore, classified into three types, and the pole shapes and anchoring devices are proposed to prevent these problems and the test results of the systems in the field are also described.

Impressed Current Systems (ICS) consist essentially of a DC power source connected to the structure to be protected and an inert anode in contact with the electrolyte. A galvanic anode is not required. Following the formation of a protective oxide film on the surface of the structure, the output current decays. Deposits of corrosion products on the anode surface restrict the current to an anode surface area of only about 50-80cm2, and it is necessary to install anode banks with an area of about 100m2 with wastage of precious metal. The performance of a system requiring an increase in current density with time can also be influenced by the loosening of the contact between the anodes and the electrolyte (M. (E) Noamy et al., 2016).

I.4.3. Design considerations

The previous sections outlined some of the more common methods for protecting structures, materials and components continually exposed to corrosive environments frequently encountered on the rail transit systems. However, even the most effective corrosion control methods, systems and procedures can only be fully effective if they are applied to components designed to properly accommodate them. The unfortunate fact is that as many additions, modifications and improvements have been made to protecting a component from corrosion, an equal or greater number of faults have been made in the design or integration of the protection methods. The following are some of the more common methods which, if possible, should be avoided entirely (O. Gilbert et al., 1982). If they cannot be avoided, consideration should be given to making other allowances which may make them less damaging.

Rail fasteners: designs which retain a fastener assembly with only one plate which is undercut or slotted and carries only half of a shorter bolt at the edge of a flange. This type of design often yields half nut and bolt assemblies, which rust into unremovable lumps.

Welded plate, arc-welded or otherwise post-welded: steel structures whose fabrication drawings appear to specify multi-pass welding. A poor alternative is reclaiming cleats bolted in place.

Coated steel construction: cantilevers or other steel structures which cannot be surface- or shot-blasted, or painted more than with a galvanizing priming coat. Painted steel structures in humid vaults or tunnels can spawn corrosion as better self-sustaining than sulphur-bearers if waxed or otherwise hydrocarbon-lubricated.

Vertical hollow structural section poles (HSS): poles with casting nests such that their bottom 20-30 cm will never drain, or if their top box is closed, even vent.

Lightly painted, sprayed or hot-dipped galvanized fittings: fittings which are thickly plated, cried or encrusted with anodic coatings.

Ductile iron fittings: 38 mm and smaller funeral supply type fittings. Copper or bronze fittings.

Copper or plastic wire, plastic insulators: wire, fittings and installed resistors used in other applications but which are not consistently compatible with transit systems.

The fights against corrosion are permanently carried out predominantly by manufacturers and service providers. Owners of huge assets and installations, such as ports, harbors, storage tanks, pipelines, airports, are investing enormous amounts of money leading to huge budgets. It is assumed that over 5% of the GNP of industrialized nations are spent for corrosion prevention, prevention and management of statically and dynamically loaded infrastructures, long live and short lived powerful machinery systems including all sorts of transport means, etc. (Hagarová et al., 2021). These amounts comprise investments for the protection in design level and for continuous control and monitoring including repair including renewals. Due to superior design ideas and rust protection measured in the design level, the possibility of corrosion is eliminated in simple parts or large installations such as propellers, crankshafts, ship hulls. It is also a common practice to install cathodic protection. Where the corroding area is modelled to bring it to the compact shape, alloyed gears were designed being higher strength than those made with […] system but being corrosion resistant. The utilization of easily available corrosion resistant materials for seawater application shows that the possibility of corrosion could be eliminated in materials selection as well (Victal do Nascimento et al., 2019). There might also be simple geometric or parameter tuning that might be more patient to corrosion: The parts exposed to severe corrosion being made extra thick, the geometry of the rod weld joints on safety containers changed to external fillet welds, larger deposit on the pressure vessel by welding, stronger plastic pipe joints in the piece of automation safety valve controlling oxidation. Measures in design level against galvanic corrosion (removing bridges, insulating splices, plastic jaisy on non-paintable cathodes, no aluminum on aluminum-alloy construction) are known widely. Approaches may still be available for each specific case as prevention against corrosion, necessity on the macro and micro alteration and optimizing were white surfaces might be obtained after manufacturing instead of brown straighter surfaces after grinding. Knowledge of body protection with superior paint taking the physical features into account.

I.4.4. Corrosion-resistant alloys

The susceptibility of metal materials to corrosion due to their chemical nature is normally high. To overcome or reduce corrosion problems, various strategies have been developed, such as alloying, paint-coated, alkali cleaning, and anodizing. Among these corrosion prevention methods, the most used techniques are based on corrosion-resistant alloys. Therefore, metal alloying is one of the most common methods for improvement against corrosion. The reason is that most metal compounds are thermochemically very stable and non-polar, thus it is energetically favorable to oxidize and solvate the metal ion rather than to oxidize the oxide. Alloying approach by sputter deposition technique has a great ability to discover new corrosion-resistant materials by preparing new alloys and searching for their chemical compositions. An early alloy development opportunity with excellent corrosion resistance was found in the field of Inconel alloys. Inconel alloy 600 has been used for a long time as a material for steam generator tubes in pressurized-water reactors (PWRs). The susceptibility of alloy 600 tubes to intergranular stress corrosion cracking (IGSCC) and pitting corrosion in primary coolant of PWRs was confirmed in mid-1980s, and numerous studies have been emphasized on improving the resistance to IGSCC and pitting corrosion (K. et al., 2010). In contrast, alloy 690 with an increased chromium content has been developed as a new PWR steam generator tube material with an excellent resistance against IGSCC, pitting corrosion, and denting. This alloy has been widely used as a steam generator tube material even in many old PWRs. Alloy 690 is a wrought nickel-chromium alloy containing a small amount of iron and manganese, which was developed for the purpose of improving the resistance against stress corrosion cracking and pitting corrosion. Its alloy compositions were optimized to maintain favorable microstructural features, which would contribute to the excellent corrosion resistance.

I.4.5. Non-metallic materials

To overcome the limitations of metallic materials in many corrosive medium applications, non-metallic materials are being investigated and developed. The use of traditional non-metallic materials, such as Wood, PVC, FRP, and Concrete, is customary. Satisfactory functional properties are obtained in a variety of applications using pigmented, reinforced plastic materials known as FRP (Fibre-Reinforced Plastics). On the other hand, plastics (thermoplastics and thermosets) are currently being investigated on their own as potential materials. The current state of polymeric materials in corrosion prevention and protection is generally summarized below.

Polymeric materials possess certain benefits over customary non-metallic materials in a variety of corrosive combination applications. These materials are lightweight, low density, ease of fabrication, and easy installation. However, utilization of polymeric materials in a corrosive environment are constrained due to their high permeability, low strength, thermal conductivity, and high thermal expansion co-efficient (Ammar et al., 2018). Combining polymeric materials with fillers generates multi-mode barrier membranes. Alternatively, combining polymeric coatings with surfactants to create nanostructured surfaces is studied to control corrosion. The major non-metallic coating types are also addressed.

A coating of active composition and its delivery mechanism significantly affect anticorrosion performance. Corrosion resistance is achieved by creating a barrier against environment agents on non-metallic substrates by curable polymeric coatings. What is more, highly active compositions such as salts of transition metals, nanoparticles, and phosphates exhibit high reactivity with corrosion sites. An uncoated metal surface would probably corrode due to initial defects of polarity or coverage of coatings. Knowing this susceptibility of corrosion, action mechanisms of active compositions are classified into cathodic or anodic inhibition types. The inhibition mechanism needs to be protective at the defect sites; otherwise, an active composition becomes detrimental to coating performance. It is shown that removing copper from unconsciously damaged poly(bisphenol A carbonate) coatings improved corrosion resistance of the surface.

I.4.6. Surface treatments

Various methods of surface treatment can be used as corrosion prevention systems. This prevents corrosion through the development of a natural oxide layer, the usage of electrochemical couple corrosion, or through applied barriers. The simplest, without any applied layers or chemicals is patination. In many cases, however, material that needs to be protected from corrosion is polished to give a bright shiny finish (J Mills and Jamali, 2010). This procedure strips away the natural oxide layer and creates a higher tendency for rapid corrosion. This suggests chemical treatment may play a role extending into the surface preparation process prior to painting. Other methods, however, include electrodeposition of metal oxide film, galvanizing, the application of a phosphate conversion coating, electroless deposition of a low deposition metal such as nickel, or treatment with corrosion inhibitors. These processes may or may not change the outer general surface finish.

Many painted surfaces exhibit generally good corrosion resistance, but blistering and delamination often occur under organic coating systems that are not applied correctly or that have been damaged. Such coatings are unable to protect the metal substrate from corrosion. Surface preparation, combined with the process of removing existing coatings, ranks as one of the most critical steps in successful coatings application. Corrosion, painting, conversion, defects, and even combinations can provide the opportunity for extensive investigation of micro- or macro-phenomena detection. A practical method of visualizing and understanding such long-range phenomena is to fuse it to a fate-controlled property. This essentially maps the underlying phenomena into a format that can be more easily recorded, interrogated, and analyzed electrochemical techniques.

Electrochemical techniques that are time-dependent in nature, such as electrochemical impedance spectroscopy (EIS), DC polarization, and galvanostatic current-pulse response, are capable of measuring the long-range effect that the defect propagation process has on barrier-related parameters (R. Tomachuk et al., 2019). Resistance estimation from impedance spectra fitting can be used to monitor the development of dissolution pits that change the macroscopic geometry of the surface at the same time. Other powerful electrochemical techniques include AC voltammetry and microelectrode-based techniques that can be used to take electrochemical measurement at a spatially resolved scale.

I.5. Corrosion inhibitors

The use of corrosion inhibitors is a practical, effective means of protecting metal surfaces from the effects of corroding agents. Corrosion inhibitors inhibit corrosion reaction from taking place by inhibiting the anodic or cathodic reactions of the corrosion process, or by decreasing the film permeability in case of passive metals (Oki and Anawe, 2015). Business establishments, industries, and farmers, therefore, progressively make use of corrosion inhibitors as a means of cutting back their losses through corrosion. Corrosion inhibitors are commonly used to protect metals of all types where human activity tends to encourage corrosion such as hot water lines, sewerage systems, chemical plant piping, farm machinery, irrigation sprinklers and equipment, and even lead pipes in buildings, from damage by corrosion. Building materials can be corroded by chemical attack causing ugly scaling and leaks in pipes or tanks. Bottled soda drinks will absorb dissolved metal oxide if left too long in a tin can. In the automotive industry expensive permanent damage from corrosion to suspensions, exhaust lines, floor pan, concomitant mechanical components, bearing and electronics is common.

In insulated environments such as tidal river systems corrosion can be accelerated due to the combination of moisture and salt application, for example. In the fossil fuel and mining industries particularly aggressive environments and equipment are commonplace. In the high tech electronics industries corrosive filament, foil, wire, ink and coating are used in everything from chips, headers, tacking devices, and bubbles in printers (Khamees Thabet et al., 2023). Corrosion inhibitors can either be organic or inorganic compounds. Organic corrosion inhibitors include heterorganic, ionic liquids, and surfactants. Inorganic inhibitors include chromates, molybdates, nitrites, phosphonates, and so forth. The literature is replete with many useful inhibitors in all categories. However there is no perfect inhibitor, and even the best inhibitor may be fairly ineffective in certain environments. Sometimes several inhibitors will be screened and tested prior to one being found which works adequately for a particular application.

I.5.1. Organic inhibitors

Corrosion of mild steel (MS) is a contending issue in various industries such as pipelines, aviation, automotive, civil structure, marine, oil and gas industry, transportation infrastructure, and water treatment. In corrosive environments, metallic corrosion can result in 19 to 23% of global economic losses or USD 1.3 trillion. Aside from lost assets, it can lead to health and safety hazards, thus posing an environmental concern. Corrosion is a consequence of the chemical process that involves the conversion of Fe2+ to more stable Fe3+ oxide forms, followed by the hydrolytic reaction that leads to the formation of corrosion products, also collectively known as rust. The aqueous medium promotes the redox activity of metal cations in a corrosion process, thus arresting corrosion is relatively easier through the inhibition of aqueous solution than the passivation of the metal surface. In view of the impending corrosion concern under aqueous medium, inhibitors are added to aqueous solutions to protect metals against corroding. To date, several research attempts have been devoted to searching for effective corrosion inhibitors. Roughly, such corrosion inhibitors are broadly classified into two categories, namely, inorganic and organic inhibitors. Inorganic inhibitors, mainly consisting of chromates and nitrites, have been restricted due to their toxicity such that research on inorganic inhibitors has almost been ceased. Given the pressing needs of the ecological concern, environmentally benign alternatives are desired. Thus, organic inhibitors have been continuously investigated in the past 80 years (Stephanie S. Carranza et al., 2021). Organic inhibitors correlate their corrosion inhibition efficiency to their adsorptive abilities onto the steel surface. Amongst various organic compounds, small molecular piecewise corrosion inhibitors have been intensively investigated. It is reported to be effective in the sub ppm range due to its low molecular weight compared to polymeric biocides. Corrosion inhibition efficiency relies on interactions between the inhibitor and the surface of the MS. In aqueous solutions, organic compounds can be adsorbed on the metal surface by several mechanisms: physical and/or chemical adsorption, formation of electrostatic bonds, or interactions between the inhibitor molecule and the metal surface. It was demonstrated that the presence of S, N, O, and P atoms in the organic skeleton has good adsorption patterns on the steel.

I.5.2. Inorganic inhibitors

Inhibitors are usually recommended for inhibition at moderate temperature (30 – 50ºC) and concentrations of the order of 10–1000mg / L. This information also applies to the commonly used steel inhibitors in acid solutions such as HCl, H 2 SO 4, HNO 3 and HF. However, it has been reported that most of the organic inhibitors used in industry and laboratories at present fail to protect the steel surface from corrosion or pickling damage by hot concentrated HCl above a temperature of 90ºC. In order to cease the effect of hot concentrated HCl on the steel surface, a patent was filed to incorporate corrosion inhibitors into the HCl solution which could essentially make it safer. Many investigators illustrated the beneficial effects of added single- and double-charged cationic surfactants on the corrosion performance of HCl inhibited by cationic surfactants to hot concentrated HCl at 90 and 98ºC.

Those surface-active organic inhibitors were easily desorbed from the steel surface and failed to protect the steel surface in hot concentrated HCl solutions.

It is well known that simultaneous inhibition with surface-active and non-surface-active (void surfactants) inhibitors is highly effective at high temperatures on the corrosion of metals exposed to all kinds of aggressive media including acids. A mathematical equation was developed to quantify the interaction of surface-active and non-surface-active inhibitors on the anodic and cathodic reactions of metal oxidation and reduction, respectively. It was theoretically confirmed that the combined inhibition with a suitable inorganic salt and a cationic surfactant is superior to the inhibition with a single inhibitor (Yang, 2021).

In this study classic inorganic salts were selected as inorganic inhibitors which provide plenty of available ion species contributing to charge neutralization or precipitation in aqueous solutions. It was first applied to investigate the efficacy of hybrid inhibition, phosphate and cationic surfactant hybrids, on hot concentrated HCl at 90ºC to cease the corrosion of steel using impressive multipronged approaches including decomposition mechanism and protection mechanism investigations. Noticeably, the combined use of cationic surfactant and phosphate salt is adaptive and cheap.

I.5.3. Biocides

Biocides are common chemicals used to mitigate microbiologically influenced corrosion (MIC) of construction materials. According to their mechanism of action, commonly used biocides can be divided into oxidizing biocides and non-oxidizing biocides. Their antibacterial characteristics are relatively strong, effective concentrations are low, and long-term action is relatively stable. However, they can also have negative effects on metal corrosion, drinking water impurities, aquatic toxic effects, and biofouling in the subsequent processing system (Shi et al., 2023).

As a result of the deep strength of microbe rejection mode, the research and development of biocides with strong reactivity and low environmental pollution is increasingly important and urgent. Commonly used biocides can be classified into oxidizing biocides, which can react with organic substances in the environment, leading to unstable bactericidal performance. In addition to the effects of dissolution time and heat, the intermediate products released by the reaction can rapidly increase metal corrosion, leading to equipment and environmental damage. A limiting pH range means that the chemisorption of

Cu hurts macromolecular surface polar groups, which can lead to reduced bactericidal performance over time.

To prolong the action time of biocides and reduce their corrosion toxicity, a new coating can be designed to effectively kill bacteria. The biocide is coated on the surface material by means of a coupling agent, and the surface polar groups react with the biocide to effectively kill bacteria. However, as the surface polar groups gradually age, it leads to the gradual loss of biocides and a gradual increase in bioadhesion capacity. At present, the dual-protection approach of using a surface coating and biocides can effectively repair and protect metal corrosion..

I.6. Monitoring and inspection

Corrosion is a major concern for asset owners in the energy and power sectors. Huge costs are dedicated to the inspection and maintenance of corrosion in industry. Corrosion accounts for 42 percent of failures in structures (Wasif et al., 2023). Corrosion is one of the biggest problems of structures, plants, piping, and other equipment in oil and gas companies. A 0.5 mm thick carbon steel pipe can fail catastrophically within five years if corrosion is not controlled. Thickness loss due to corrosion might lead to catastrophic consequences if not detected and mitigated in time. Detection of corrosion at an early stage and continuous monitoring are imperative to avoid these failures. Monitoring and/or inspecting corrosion is intended to keep track of wall loss over time. Monitoring involves continuous data acquisition on the state of the component, providing continuous information on the status of the component. A number of corrosion monitoring techniques are employed in the industry. Intrusive techniques such as weight loss coupons, electrical resistance probes, and electrical impedance spectroscopy involve measurement of corrosion rate by exposing the coupons or probes to the flow conditions. Non-intrusive methods such as ultrasonic, guided waves, surface acoustic waves, optical fibers, and capacitance measurement are installed on the component for corrosion monitoring. Guided wave transducers can screen large pipe lengths and cover 360° of the pipe circumference. The most commonly used corrosion monitoring device is the ultrasonic thickness gauge.

The maintenance of critical metal structures can be costly and time-consuming due to excessive inspection and recoating maintenance (Latif et al., 2020). The commonly practiced scheme for maintenance is Scheduled Based Maintenance (SBM), which is carried out at regular intervals independent of the structure's condition. This often results in unnecessary maintenance and has led to studies into alternative approaches. These studies have resulted in the implementation of Condition

Based Maintenance (CBM), where the condition of the structure indicates that maintenance is necessary. Sensor technology can provide an efficient solution for condition monitoring of structures operating at remote locations. Various corrosion sensors have been developed and are characterised as direct and indirect corrosion monitoring techniques. The direct monitoring technique involves the measurement of potential or current resulting from corrosion/electrochemical reactions. Corrosion coupons, electrochemical impedance spectroscopy, electrical resistance, and potential measurement using linear polarisation are examples of direct corrosion monitoring techniques. Indirect corrosion monitoring techniques are based on an outcome resulting from a corrosion reaction. Radiography and ultrasonic testing are common indirect and non-intrusive corrosion monitoring techniques. The electrical resistance method measures the change in resistance caused by metal loss. The rate of corrosion can be measured at any time but requires calibration based on the properties of the structural material. Electrochemical Impedance Spectroscopy is used to measure the corrosion rate of the metal structure as well as any corrosion occurring under the coating. Linear Polarisation Resistance (LPR) method provides a direct and instantaneous determination of corrosion rate for real-time structural monitoring.

I.6.1. Visual inspection

The visual inspection of structures for corrosion defects is most commonly employed in civil engineering applications, although it is also used in most applications where a maintenance inspection of structural integrity is required. The engineer or inspector looks at the structure and notes where rusting or other corrosion damage has occurred. The inspection is subjective, requiring experience to identify potential corrosion problems. Special camera lenses and photomicrograph techniques are often employed to facilitate the inspection task. Development of non-contact techniques to facilitate distance inspections and to ease the task visually will lead to uniform inspections (Katunin et al., 2022). To reduce the chances of viewing the structure wrongly, the development of automatic techniques may be employed, depositing paints or dyes on good surfaces, which can be viewed.

Inspection of visually accessible criteria is most effective when the dwelling is still reasonably young, as the initial corrosion issues will normally be located at unprotected or poorly coated surfaces where access is straightforward. Rapid inspection of hot zones is not as straightforward, and the rate at which such corrosion tickets travel their system means that if they begin to grow the risk to the structure is frequently severe. Field testing of methods for immediate risk is required (Zajec et al., 2018). Many techniques are available to indicate the presence of corrosion pits: eddy current systems, magnetic inductance systems, and electromagnetic acoustic technique systems. The physical principles employed in each technique are diverse, and the various techniques have separate advantages and disadvantages related to depth of inspection, sensitivity, and speed, all issues which are affected by the structure being inspected. Recent research continues to search for better ways to detect corrosion defects.

I.6.2. Ultrasonic testing

Ultrasonic testing (UT) is based on the propagation of ultrasonic waves through ferromagnetic material, commonly used in the evaluation of the mechanical characteristics of pipeline thermal treatment. The threshold frequency of elastic wave propagation depends on the physical structure and the properties of the test objects and the instruments. This choice leads to a high-efficiency ultrasonic intelligent diagnostic tool for steel pipe structure micromechanics. This tool is comprised of two groups in the following order: a computer with special measuring software and hardware, and the ultrasonic probe with piezoelectric oscillators. An ultrasonic oscillator tests the pipe diameter and thickness. It also transfers the signal between the oscillators and the computer using a cable. The windows of the measurement have the shape of an extended rectangle, covering a few hundred metric tubes iterations. The hardware transfers the real-time signal as a sequence into memory files, allowing the user to observe the intensity distribution in time. The time to distance coordinate conversion shares the information on waves between the interfaces. The software begins at a console window to set measuring parameters. These can be pipe diameter and thickness, probe location, signal frequency response, and signal amplitude. They can also be conditions to test regimes and signal filtering.

The theoretical basics of the acoustic wave approach are presented in many published papers. The dimensionless system is convenient and allows physical characteristic parameters and behavior of the generic objects to be analyzed. At the first stage of the length scale model construction, the threshold frequencies were calculated as a function of pipe diameter and thickness. Differently from conventional applicability, UT methods are sensitive not only to the back wall but also to corrosion holes and additional artificial structures. Effectiveness in testing and possibility of obtaining quality estimates of the probability of the pipeline condition state are demonstrated based on the published log data. Controlling the acoustic field in water and the transformation of the wave field in a steel pipe structure are considered as analytical and numerical problems. The energy of waves propagated in a water layer is concentrated by an input type transducer. A pipe structure with arbitral curvatures influences the time and type of transmitted waves. Some acoustic waves are used in acoustic imaging and control of the pipe structure state. A possibility of reconstructing the imitated structure and of estimating the impediment of transit waves using the singular value technique is pointed out.

I.6.3. Electrochemical methods

Electrochemical techniques are widely used to study corrosion mechanisms and the effect of inhibitors on the corrosion process. This section introduces two major electrochemical techniques. The first one is primarily used to study the electrochemical behavior of mild steel in a chloride environment. In particular, the most popular laboratory methods used are described. Afterward, a brief introduction to some experience, limitations and advantages about the electrochemical corrosion testing techniques used in corrosion research and industry is given.

Electrochemical Impedance Spectroscopy (EIS) has become the most powerful electrochemical technique in the characterization of the state of a corroding system, whether passive or active. EIS is a non-destructive technique and is capable of measuring the entire impedance spectrum of a working electrode, allowing a quantitative interpretation of the corrosion processes occurring in the system. In general, it is a very flexible method and can be adapted to many experimental environments. However, its versatility implies a steep learning curve that is prone to operator failure if the learner tackles too many convoluted tasks simultaneously. EIS measurements can take up to several hours if a large frequency range is acquired with a high resolution. Errors made in the interpretation of results can be very costly in both time and money.

Although potentiodynamic polarization (PP) curves are easy to obtain and interpret, it is a less serviceable technique than EIS since the systems must be disturbed to obtain a new set of results. Data can be collected continuously or at fixed time intervals, allowing for a sensitive monitoring of slow changes in the system. Nevertheless, the rapid changes that corrosion systems can undergo may escape observation unless inspiration is used to test different setups or new experimental configurations. Since any step in the test procedure may influence the future behavior of the system, there is also a steep learning curve. Equipment that manages to get experimental data autonomously is very expensive and requires a considerable amount of time to train operators in its use. An alternative solution is to supplement the non-invasive EIS measurements with post-mortem analyses of samples that have shown some change.

I.7. Case studies

Corrosion affects all the industries and even municipal services without ceasing and renews it. This talk will present three case studies in both industrial and municipal service (Oki and Anawe, 2015). In one case a large underground concrete vessel was completely renewed, ahead of time due to unforeseen conditions. In the second case blackened paved roads due to snow melting chemicals have been renewed ahead of time due to corrosion, which are now restructured to prolong life. In the third case, due to poor decisions and design flaws, many key pipes in a large industrial plant have failed due to internal corrosion and prevention measures have been developed to restore expected life. Guards against corrosion consist of: (1) Choice of construction materials, (2) Type of corrosion protective foreseen, (3) The capability of maintenance for a given solution and (4) Cost of the solution over the expected lifetime of the construction. In particular the first choice (1) is often taken as a compromise, foreseeing as possible loss of lifetime (due to corrosion) as smaller as possible compared to the overall expected life. Commodities must also go through municipal and industrial pipelines to be moved. Many of these pipelines are made of steel and are prone to corrosion. As a matter of fact, all are, one must only take into consideration the environmental conditions they are exposed to.

In municipalities those constructed in early 1900 are most extensive ones and constantly subjected to a high degree of pH variation, heavy bacterial depositions sometimes including sulphur reducing bacteria, most extensive dumping of hot water excesses from industrial processes – to name a few reasons forces conduits to drain out their own build-up deposits, and paving spray white paint on pavements is clearly not enough to avert road blackening. On industrial level, well-designed RHEO pipes must carry the most aggressive compounds through an anticipated long life of service. The degree of corrosion of a metal is largely dependent on the environment in which it is put to use. For example, a metal which does not corrode appreciably in one region of the world may rapidly fail in another. Even within the same region, it may behave differently in different locations. There are many cases on record of metal failures attributable to improper use or location.

I.7.1. Industrial applications

Historically, metal deterioration from environmental exposure has been dispositional ailment of civilization and ensures extensive damage and economic loss. It covers most of the metals and their alloys used in industrial, power generation plants, automobile, petrochemical, chemical processing plants, irrigation works, and agricultural sectors, leading to accidental failure, human morbidity or fatality, and environmental degradation. Corrosion may occur in different types, rates, and mechanisms in varying media and elements. A corrosion is predominantly electrochemical interaction between metal and the surrounding atmosphere or environment in the presence of moisture acting as an electrolyte resulting in metal deterioration. Steel, cast iron, and aluminum alloys predominantly corrode under uniformly distributed and mostly highly predictable atmospheric fallout. Corrosion inhibitors reduce or prevent dissolution of the anodic areas and increase passivation of the cathodic sites. Corrosion inhibitors are classified into metals, oxidation states, anions, and organic and inorganic compounds. Industrial sectors covering industrial infrastructures, machines and equipment, power and desalination plants, oil and gas piping, petrochemical, sugar, pulp and paper, and textile industries suffer serious economic loss from metal deterioration due to process needs (Oki and Anawe, 2015). Ford Motor Company reported corrosion cost exceeding USD 1 billion; National Bureau of Standards estimated national corrosion cost exceeding 15% of the GNP. Individual companies report corrosion costs exceeding 3–6% sales revenues.

Agricultural industries are categorized into farms, farm machine and equipment fabrication, tractor and farm machinery assembly, sugar, grain processing and handling, fertilizer and chemical manufacturing, and agrochemical formulation, packing, and marketing industries. Farm machinery and equipment fabrication, assembly, and repair units fabricate, recondition, or modify seasonal machinery, and cover crane, wagon, harrow, wire spinner frame, tube wells, fertilizers sprinkling manures and pesticides tankers, etc. These units need good corrosion protection with the coding metals or non-flaking paints for long-term use. Soiling and exposure to field elements deteriorate their paint. Pertinent consecutive washing with detergent water followed by thorough rinsing and drying ensures good paint adherence. Coating metals like Zn or Al may ensure good corrosion protection in aggressive environments. Similarly, protection of cast metals by hot dip galvanization is common.

I.7.2. Infrastructure projects

Infrastructure projects and the subsequent urban issues of aesthetics have come to the fore recently. Unless it is a pretty or spectacular design, to most city dwellers, structures are merely facilities used to travel or tell stories on. Aesthetic consideration in civil engineering structures has been long neglected. A project exposed to uncontrolled external conditions tends to suffer corrosion, which destroys both safety and aesthetics. Corrosion is an electrochemical process that involves the loss of metals. Given the existence of atmospheric moisture, salt, and corrosive chemicals, almost all metals tend to corrode even in normal environments, let alone extreme environments. In order to keep these structures from corroding and ruining the beauty of the city, corrosion-protective paint systems are needed. However, construction costs for these structures have been wrongly controlled for decades, simply to be the lowest bid. Therefore, protective coatings, whose long-term performances have been conspicuously questioned and are therefore not adopted, are employed, bringing about corrosion problems. Corrosion problems of civil engineering structures, both aesthetic and safety issues, get more severe as these structures get older, and corrosion-protective systems, especially paint systems, need to be considered and analyzed regarding these issues. (O. Gilbert et al., 1982) Superior designs, quality inspections, modern equipment, and adequate construction procedures are not sufficient to maintain the integrity and appearance of a structure without a proper paint system. Such a structure will sustain from mere chemical and electrochemical attacks as long as its paint system has been selected adequately and is well applied and inspected. While the city gets older, quality inspections can become relaxed and even corroded areas are hidden away regardless of their size, bringing about great aesthetic problems indicative of negligence. Considering corrosion problems in the design stage will allow preventive measures to be proposed for avoiding or improving them at inception. A design must exclude valuable elements from observable regions as long as they are technically sufficient. The life span of a structure should be sufficiently analyzed, utilizing modern analysis tools. Replacement materials must be selected and spelled out for the selected design if the life span is insufficient. Otherwise, a protective coating and its maintenance should be considered to prolong life and hide corrosion.

I.7.3. Marine environments

There are various types of corrosion common to ships but the one with which we are concerned is ‘galvanic corrosion’ in which one metal (the steel hull) corrodes quickly and another metal (the Nickel-Aluminium-Bronze propeller) more slowly. In this corrosion, the electrons flow through the sea water which acts as a good electrolyte. This electron flow results in a ‘corrosion current’. Because these currents flow for long distances through the water and through the fabric of the ship, they generate appreciable magnetic fields well away from the ship. In general, there are five methods for controlling the corrosion of metals in sea water. The most common defence mechanism is the painting of the hull with a protective coating which provides a physical barrier to the sea water and hence impedes the ion and electron movement. This is a principle that is still heavily relied upon today (J Allan, 2004) although modern day coatings serve three purposes: to protect the hull from corrosion, to prevent the build up of marine life on the hull which may create an environment that will aggravate any corrosive attack, and the coatings used in the modern era to prevent corrosion of vessels have obviously advanced. Until recently the general practice was to only coat the hull as the turbulence of the sea water around the propeller and rudder made it extremely difficult to apply a coating to these. Recent developments in the adhesive properties of the coatings has meant that several trials are currently underway testing new propeller coatings. The sacrificial anode cathodic protection (SACP) system was the original one to use the CP principle.

With the advent of the first metal hulled ships, the problem of corrosion arose. The welded steel hulls imparted a level of integrity unlike for example the timber and riveted ships but also carried the susceptibility to new forms of damage deterioration. In a ship, hull corrosion can result in expensive repairs, loss of cargo, contamination, dry dock delay, insurance claims, and personal injury or loss of life. One of the most serious forms of hull deterioration occurring globally is the galvanic/electrolytic corrosion of metal bottom ships and the resultant 'undercutting'. Many vessels suffer from rapid corrosion of the hull, leaving unprotected metal surfaces. This 'under-cutting' of the coating by corrosion products expands and lifts the protective barrier leaving track contamination to the underlying surface.

I.8. Future trends in corrosion prevention

The corrosion protection methods these days mainly can be classified into two effective ways: the passive or barrier coating approaches and the cathodic protection technique. A great deal of passive or barrier coating materials that have been developed to protect the metal surface against corrosion. However, these materials don't work well long-term particularly if there are physical defects such as pinholes, cracks, scratches or even surface imperfections. This is due to the fact that once these coatings break down, metals are in contact with electrolytes and natural corrosion mechanisms re-initiate (Chowwanonthapunya et al., 2016). In this regard, the cathodic protection techniques can mitigate corrosion quite well by the electrochemical approach. This electrochemical technique can simply be applied to 20,000 square meter land well-maintained proximately in 30 years by one cathodic protection station. However, it does require frequent monitoring and maintenance services which are nets too high.

As a matter of fact, the preventive methods are usually selected based on the metal types and the environmental condition. Therefore, they have to function well across a wide temperature and humidity ranges. Aggression from the environment is the most essential factor to be considered in selecting corrosion prevention methods. For example, in the coastal environment amphoteric metals like aluminum and alloys as well as zinc-plated steels suffer from severe corrosions even in low industrial and urban pollution, this is due to the not-high but pH of the seawater, which produces neutral solutions that are beneficial to the initiation of pitting corrosion at high temperature (Oki and Anawe, 2015). If the coastal impact is severe under the arid condition i.e. the short and scarce rain period and sunshine droplets, the selected improvement methods should be resistant to the high salinity, low humidity and large temperature. In the industrial environment, an optimum pH of 4.0 can accelerate the corrosion of gray and spheroidal cast irons, mild steels and copper alloys pipes, while this limit can be 11 to carbon steels.

I.8.1. Nanotechnology

Specialized nanostructured surfaces can repel water droplets, resulting in a “lotus effect” from bionic surfaces that reduce water adhesion due to high surface energy and contact angle. The self-cleaning capabilities of these surfaces reduce the accumulation of dirt, pollutants, and microbes. Superhydrophobic surfaces have garnered interest in various fields due to increasing requirements for cleanliness, hygiene, and water repellency. These surfaces exhibit many advantages, making them widely used in maritime, photovoltaic, automotive, aerospace, oil and gas, civil, and medical industries.

Hydrophobic surfaces repel water; superhydrophobic surfaces exhibit this property more effectively, resulting in a water contact angle of 150° or greater, making the surface appear almost dry. Water droplets can easily slide down, removing dirt, dust, and pollutants and preventing the accumulation of microbes. The most common construction method for superhydrophobic surfaces is chemical synthesis; however, chemical processes can be costly, complicated, and environmentally harmful. A physical coating method could provide hydrophobicity on metal surfaces to avoid higher costs. Using a superhydrophobic coating on metals such as aluminum, iron, and copper can prevent corrosion without the additional expense and hazard of chemicals.

Corrosion is a large economic issue in many industries. Modern factories spend an estimated five percent of their capital on corrosion prevention. Corrosion occurs when water, acid, or a salt solution reacts with metal or metal alloys; ions move between the anode and cathode in a saline solution. Rust from iron oxide is an example of corrosion through oxidation; an oxide layer can block corrosion and maintain the integrity of the metal. The rate of corrosion can be increased by ion migration through high conductivity due to impurities, galvanic corrosion through ion exchange, and aciddissolving action. The latter two causes are rare in practical cases. It is also essential to provide a coating to prevent ionic movement on the surface of metals and allow a longer-standing lifespan (Haji-Savameri et al., 2022). Coatings can be polymeric paints, ceramic paints, or a combination. Polymeric coatings can reduce the coating weight but can corrode in harsh environments, making them ineffective. A solution is to use a combination of coatings by blending polymers and ceramics to create a nanocomposite coating with nanoparticles function to repel water. A nanocomposite coating of epoxy-acrylate and silica nanoparticles is created through a hybrid polishing and sandwich method and studied with a salt spray test (Ahmed et al., 2018).

I.8.2. Smart coatings

Smart coatings that combine sensing and response properties are investigated. This technology has been successfully applied to water and temperature sensors based on the swelling of hydrogel and electrochemical sensing of rusting based on pH measurement. Thus, copolymer or terpolymer swelling coatings are designed to sense water, while exhibiting anticorrosion properties when keeping the substrate dry (Feng et al., 2023). A self-healing system based on hydroxymethylated polyethylene with incorporated pH-sensitive carbon nanofiber electrodes was validated to detect the presence and site of corrosive agents. An electrochemical detection system based on APTES functionalized silicon reinforcement electrodes rejecting small interference-causing ions that detects the presence of Eaton in concrete structures was also developed. Novel hydrophobic polymers have been demonstrated to be resistant to both inorganic and organic dissolve (Uddin Ammar et al., 2018).

Complex coatings that provide multiple functions are also investigated. Exceptional resistance against both thermal and chemical degradation, automatic droplets recoiling and rolling-off of polymeric surfaces produced from antiquated bike handles, multi-thermal switches based on polymeric microstructures densely coated with polypyrrole for automatic operation, reversible switch of state from sticky to low adhesive level as water droplets are deposited on polymeric surfaces after laser irradiation, easy removal of super soluble thin layer of polymeric surfaces are some applications that have been developed. A modification-resistant switch of wettability using nanotextured poly(dimethyl siloxane) based on air entrapment is also ideal for self-cleaning applications. Sieving pressure sensitive switch based on origami mechanism provides a novel sensor for counting the number of pigs let through. Complaint filters, spring-loaded switches, aligners, and mini cranes that can transport sources are also developed. Therefore, development of smart coatings that combine high chemical resistance with a solid sense of pH is required.

I.8.3. Sustainable practices

Corrosion follows the 12 principles of "green chemistry," which were introduced to chemists and chemical engineers in 1998. These principles have been reinforced and adapted for "green" activities by other communities, including those of corrosion engineers. "Green" technologies encompass a whole family of methods, including new products, processes, or services that reduce pollution at the source by reducing or eliminating hazardous substances (Feron et al., 2018). Therefore, these principles arise in a general environment of sustainable development. When dealing with corrosion, it is thus expected that the products and processes, without forgetting their use, reduce waste and pollution, are energy- and resource-efficient, minimize the use of hazardous substances, and produce active corrosion inhibitors, protective coatings, and corrosion-resistant materials. The principles of "green" corrosion are the following: reduce derivatives; design for innocuous degradation; life cycle management; pollution prevention.

Reduce derivatives: This principle means that, as far as possible, over-reaction should not be done, and reactions in column should be avoided, to have as few steps as possible. A reaction with several steps means more reagents are needed, and it is the number of steps that generates waste. Galvanization is the process of coating iron and steel with zinc that is widely used in applications where corrosion resistance is needed. In the traditional method of galvanization, the steel is immersed in a solution of zinc salt, which leads to the formation of a corrosion-resistant layer. New process of galvanization: hot-dip galvanization. At high temperature, the iron forms a solid solution with zinc, so the iron in contact with the zinc lamina reacts and iron-zinc alloys are formed; as the steel is immersed in bubble zinc, hydrogen gas is generated. With this electrolysis, less chemical reagents are introduced.

I.9. Economic impact of corrosion

Corrosion is a chemical reaction affecting materials used for most products and structures. The corrosion has always been an important problem from the economic viewpoint. The cost of corrosion of metallic products is increasing more than before, as the metallic materials are widely used in various products and structures. It is generally agreed that the cost of corrosion is a multiple of the prices for the corrosion prevention techniques. Estimation and analysis of the cost of corrosion are, therefore, necessary in order to save funds for corrosion prevention. The purpose of this project is to estimate the cost of corrosion of metallic products in Federal University of Agriculture, Abeokuta (FUNAAB). Some design and construction materials degrading due to environmental and operational problems become unable to perform their intended function before the termination of their design life. They lose their functional capability and effectiveness. Such loss of functional capability and effectiveness is generically termed degradation (Orisanmi et al., 2017).

Corrosion is one of the degrade mechanisms affecting metallic materials. It is an electrochemical process whereby metal loses its metallic properties such as luster, brilliance, hardness, rigidity, and tensile strength. Most parts degrade at the corner or cutting edges, exhibiting a step-like film of oxidation. Several factors influence how corrosion reacts with the materials. Salts and acids accelerate the corrosion process. Other sources of degradation are cleaning solvents, high and low pH materials. Moisture is one of the most important contributors to corrosion. Atmospheric humidity accelerates corrosion reaction as a conductive medium (Chowwanonthapunya et al., 2016). Moreover, failure of product and structures due to corrosion results in the loss of human lives and a large cost impact on nation wellbeing. The process and information on the estimation and analysis of losses in life and money due to corrosive degradation need to be collated and made available to the industry. Therefore, this project is aimed at setting this process and information in a framework to assist in the estimation and analysis of corrosion costs. Other corrosion types, which have more direct effects in-line with human lives, like cracking & embrittlement, will also be considered if resources allow.

I.9.1. Cost of corrosion

Corrosion is the gradual destruction of materials due to interaction with their environment. In a broader sense, it is a deterioration of the state of materials from a desired state. Corrosion is everywhere and it is costly, contributing an average of 5% of GNP loss in developed countries. Typically, about 75% of the cost requires a cleaning treatment alone. Therefore, it is of great importance to understand, estimate, and control the cost of corrosion. Corrosion costs are relatively easy to estimate for medium- and large-scale enterprises, but empirical estimations or repeated statistics would often lead to a large error for small-scale businesses. Very few reliable methods can be referred to for estimating corrosion costs in these small businesses. In addition, the estimates for the corrosive medium rely heavily on subjective judgment and require a considerable amount of experience and knowledge, which would typically be lacking for noncrude jobs. The long-term study of a case project in which the cost of corrosion in a small-scale enterprise is analyzed to estimate costs produced and find the correct treatment mode. Among the cleaning treatment modes, the cost of soaking in a caustic soda plus a sand blasting treatment is estimated as smaller than that of others. The cost treatment mode provides 37% (rounded to integer) of reductive on the total cost compared to that of the referenced mode. The high cleaning efficiency is helpful for the prediction of the cleaning cost. The cost estimation can also be undertaken in chemical industries, where the corrosion of pipes is very serious. (Orisanmi et al., 2017) The analysis shows that the larger the pipe size, the more corrosive acid would be needed to refine it. Further, it is of great value to find heat eliminations in processing intense heat transfer pipes, which would lead to noise and high running cost once corroded.

I.9.2. Investment in prevention

Preventing corrosion is a process by activity that prevents, resists, or slows down corrosion of material loss. The maintenance of coating surface, the selection of less corrosion resistant material, and the proper cathodic protection techniques are preventive measures that have become important policy concerns. Such actions may require considerable advanced investment. Therefore, this economic consideration guideline aims to provide an initial guideline for investment in corrosion prevention. The guideline presents preventive methods and outlines the selection flowchart suggestion.

The sources of corrosion are either the positive or the negative terminal of the current. The corrosion protection techniques center on the concepts of the electrochemical reaction. By decreasing the rate of electrons released from the anode, it can mitigate the corrosion problem. Cathodic protection is a method that decreases the rate of anode activity. The prevention of the electrochemical contact between metal and the electrolytes is another useful method. Barrier coating is to stop such contact at all. In addition, low cost corrodible material shield is utilized. Induced current protection is a well-designated method that can cheaply stop activity by preventing the supply of electrons. However, this protection is time limited. The material loss of the shielded site may severely disturb its operation. Both concepts can bring three common corrosion protection methods.

Barrier Coating material is to stop, in one way or another, the direct contact between the metal and the electrolyte. Once the surface is coated adequately, such contact is unavailable. However, after a certain period, the coating may be damaged and maintenance activities are needed to recover the effectiveness of the coating.

Material Selection is the less corrosion resistant one for the financial concern (Chowwanonthapunya et al., 2016). Routine inspection and proper maintenance can prolong the service life of the less corrosion resistant material.

I.9.3. Regulatory implications

Corrosion is an electrochemical process that causes a deterioration of metal due to host environment. This deterioration manifests as rust, pits, crevice corrosion, stress corrosion cracking, etc. Such corrosion attacks can cause structural and service failures, economic losses, increased malfunctions of systems and services, loss of service integrity, and environmental hazards (O. Gilbert et al., 1982). Thus, it is important to have a corrosion prevention method.

Some corrosion prevention methods can be conventional surface preparation and coatings; cathodic protection; corrosion inhibitors; paint systems modification; non-intrusive surface treatment; biochemicals and microbicides. In the hope to avoid losing time in different degradation phenomena, the new tools are given in the methods of preventive maintenance, corrosion evaluation and monitoring, and of laboratory tests of coating and paint formulation performance.

It has been well known that about 70% of corrosion problems are due to thermal shock expected during the transportation of vessels. This limits the use of high-performance materials for vessels, on which investigations for sharper gradients, fludization, or complex cooling methods are in progress. The approaches include pot experiments, such as ph-sweep runs with agricultural soils and agricultural crops, drainage-based methods to divert flow from vessels, bioaerated column reactors with ph-gradient operations, or steep wave generators for clay transport.

I.10. Conclusion

Corrosion is defined as a process of wear/ deterioration of a metal due to the electrochemical effect of the environment. In general, prevention methods can be categorized into two main approaches: corrosion resistant material selection and corrosion protection methods (Chowwanonthapunya et al., 2016). Material selection can select a naturally corrosion resistant material to minimize the corrosion problem or to choose a corrosion susceptible material, which will lead to lower capital expenditure and at the same time higher maintenance cost. This approach is therefore not always applicable and other protection systems or methods should be established.

Protection methods can be passive or active. The passive approach is normally based on the prevention of corrosion influencing environmental factors (the absence of moisture, pollutants, salts, oxygen etc.), whilst active approaches include methods to reduce the rate of the corrosion process, mostly based on electrochemical principles (including anodic and cathodic protection). There are a variety of existing practices along this latter approach, even not covered in this document. The concept is relatively simple, galvanic corrosion protection is based on the use of sacrificial metals which are more electrochemically active than the metal to be protected. Impressed current methods include rectifiers or alternating current anodes, such as doped semiconductors or inert metal oxides and are therefore more complex and costly.

Corrosion effects are usually more severe indoors, as environmental conditions are better controlled and aggravated by the use of liquid agrochemicals, acidic fertilizers and herbicides/formulations and greater reliance on electrical equipment and hence risk of stray currents through earthing and or bonding failures. Protection methods include chemical methods (the use of corrosion inhibitors in agrochemical formulations), coatings (protective films, paints, galvanizing, powder coating etc.), and galvanic (zinc or aluminum foil strips bonded to metal structures) or impressed current anode systems (Oki and Anawe, 2015).

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CHAPTER II

DESIGN PRINCIPLES

Chapter II : Design principles

II.1. Introduction

When designing corrosion-resistant structures, the best strategy is to implement numerous simple principles during manufacturing, execution, and maintenance. Particular attention should be paid to the structure is difficult or impossible to maintain and the protective systems do not have enough durability. Basic topics connected with corrosion should be included in the training of all technicians who will later worry about the design, manufacture, and maintenance of the metal structures (Gómez and Lana Villarreal, 2008). The structure and the atmosphere must be in such a manner that the greatest prevention is ensured. For instance, all kinds of nooks which aid the condensation phenomena in the atmosphere and the differential aeration in submerged and buried structures must be avoided. Likewise, electrical contact between different metals should be avoided in order to prevent galvanic corrosion; it should be taken into consideration that this sort of insulation complicates the tasks of maintenance, making them more difficult and costly, multiplying faults and therefore potentially leading to failures as a consequence (Cascini et al., 2014).

Another simple principle is to facilitate drainage of liquids in tanks and storage reservoirs. It is also important to provide good access for maintenance operations. In flour or sugar silos, for example, one must make sure the filling mouths are located far from the walls to avoid the powder's piling up. In the same way, heaters must be located so that they do not overheat the walls. In conduits through which hot gases ascend, thermal condensation must be avoided to prevent corrosion phenomena due to the formation of corrosive liquid gases. Excess turbulence must be avoided to prevent erosion and cavitation. It is better to avoid having to substitute elements which are presumed to have very short service lives, although it is sometimes unavoidable. In closed circuits, it would be advantageous to remove dissolved oxygen in the electrolyte, preventing its entrance into circuits by exposing them to the atmosphere. On the other hand, care must be taken to ensure aeration and the presence of oxidants in passive metals and alloys.

Passive films of metal oxides present in the most commonly used materials (aluminum, cavern, titanium, and stainless steels) protect against corrosion by growing spontaneously.

Storing them in a reduced atmosphere generates precious metals; a slight thickness increase will prevent them from being attacked. A wide variety of protective measures are fitted for galvanic protection. This method of prevention and mitigation of corrosion is the most widely used. It is feasible to reduce or prevent corrosion of any metal or alloy exposed to an aqueous electrolyte. A free electric charge will loosely bond to the electrocathode preventing oxidation; in the case of the anode an oxide film will grow rapidly, isolating the metal from the electrolyte.

II.2. Preventive design strategies

Shading brings benefits in solar paths for large oblique angles. On these sides, shading can be achieved by extending the roof overhang or creating a vertical element. Properly placed shading systems can also reduce the temperature inside the building by preventing beam radiation from penetrating the interior space of the building.

Overhangs, shading louvres, fins, etc., resist the entry of sunlight directly onto the glass itself. Mechanical sunshades attached to the building have less maintenance requirements than glazing systems. They may have changing sunlight incidence angles on their surfaces. Specialist analysis may be necessary for complex façade curvatures or high-performance requirements.

Shading devices are required to comply with local regulations where buildings are erected in proximity to each other. They can also improve the aesthetics of a building's façade while contributing to its thermal performance. While they can substantially reduce vertical surface irradiance, unshaded surfaces receive higher levels of horizontal and diffuse irradiance.

Most building codes require that buildings do not shade adjoining properties too much. Shading a building can modify both its indoor environment and the performance of its envelope. Glazing systems and shading technologies, well-coordinated with the building structure, allow building design to minimize energy consumption while providing adequate thermal comfort for occupants.

Buildings are primarily designed to be conditioned, engineered environments. Effective methods exist to minimize unwanted energy demand for conditioning, but operation of heating, cooling, and lighting systems can be costly, inefficient, and environmentally damaging. With a good understanding of both climate and building design practices, and correct orientation of walls and roof overhangs, a major proportion of the need for heating and cooling can be eliminated.

II.3. Durability considerations

Corrosion is one of the main threats affecting the durability and reliability of structures and infrastructure. From a structural point of view, corrosion of the metallic parts leads to the loss of the cross-section of the elements composing the structure, which directly affects its reliability and safety. Since corrosion is the consequence of a chemical and electrochemical process that can unfold over long timescales, this topic is typically part of the robustness or durability checks. Structural robustness refers to the capability of a structure of still being resistant despite an unusual load or damage that reduces its bearing capacity. Durability refers to the capability of a structure to withstand the action of environmental agents over time. The preservation of corrosion protection systems is another aspect that may be considered in this category (Cascini et al., 2014).

Both robustness and durability depend on parameters that may vary in time. For this reason, strength models should be used to assess these issues quantitatively in order to evaluate the actual reliability of the structure or its components. For this reason, both issues are traditionally treated as a second level of safety, following the structural safety check (i.e., limiting states scenarios), and the approach is similar for both. The first step is to define the design situations to analyze. For durability issues, the characterization of the specific environmental actions and the analysis of their effects over time should be considered. Afterward, an analysis of uncertainty is made and the necessary models (i.e., actions, resistances, etc.) are defined. Finally, the results of the analyses are presented and commented on (zhongxiaoping et al., 2019).

II.4. Corrosion-resistant design techniques

Corrosion risks increase with the size of a structure, with projects hundreds of meters long being particularly critical. An additional but controllable factor is the aggressiveness of the environment. Structures built in salt water or with considerable levels of carbon dioxide or sulfur dioxide face high corrosion risk. Moreover, the corrosion risks for design and construction of structures shall be a team effort where various disciplines in engineering must contribute personal expertise. Where structures are difficult or impossible to maintain, either because of their sophistication or great height, or where protection systems do not ensure a sufficiently longer service life, designs that minimize the effect of corrosion are indispensable.

Designing the structures, keeping in mind the service conditions and limiting factors permits simplicity and adaptability. This would, in turn, permit ease of construction and effective repairs and maintenance as and when necessary (Rzeszut et al., 2016). Structural engineers intentionally avoid some situations and configurations known to cause difficulty; designers must be extra alert to their possibility during design. There are many specific details that design engineers should be aware of. Care must be taken to study these situations in the context of the particular structure, design, and materials on hand.

Other, often whimsical details besides the specific ones mentioned have made trouble. Architects often dictate design elements. These must be checked for effects on corrosively and constructability. Design elements such as moats and spouts have been used whimsically, complicating the construction. Designs partly or wholly lift off the ground have shifted maintenance labor costs from steel and paint workers to masons. Similarly, decorative elements such as stone cladding must have a straightforward maintenance plan if they are to be used (Gómez and Lana Villarreal, 2008).

II.5. Cathodic protection

Before describing the design criteria for cathodic protection, it must first be emphasized that, at other sites, areas and categories of structures, an alternative design approach may be favored and adopted (Oleiwi et al., 2018). Cathodic protection, impressed current systems, metallic anodes, sacrificial anodes, and design method elicits a plethora of different specifications and practices for cathodic protection in various parts of the world. Traditionally, codes emphasize recommendations and guidance for design combined with limits on materials and construction, monitoring, especially for the use and current output of different protective systems. Some codes also emphasize the assessment of the state of the art of components of special attention, such as monitoring systems, control units, and polarizable protective surfaces in the steel-concrete environment.

Examples illustrate what might be used, ranging from standard detailed clauses to clamps with system output and levels of steel corrosion rates corresponding for various configurations based on measured potentials. Concerns and recommended practices also cover use of ground bed and protection against lightning strikes. All such examples address systems which are either existing and operating or new and to be implemented. However, design for cathodic protection over a 50 year design life is comparatively poorly covered in the literature, given the effort devoted to this topic by the committees. Moreover, designers and inspectors experienced in cathodic protection installations-or perhaps, better, installation procedures for cathodic protection systems-could have great difficulty identifying the proper codes and complying with them, as stated by other designers.

During the last two decades and especially after 2000, the participated in or independently undertook a major effort towards developing a very comprehensive design methodology for a variety of types and installations of cathodic protection systems. This methodology includes flow charts whose approximate suitability could be evaluated separately for various types of systems. However, the initial stages of this methodology concerned only the most basic cathodic protection design criteria.

II.6. Corrosion inhibitors

This term corrosion inhibitors means chemicals that prevent, or slow, the undesirable characteristic called corrosion as a process. Inhibitors do not eliminate corrosion, rather they manage the corrosion rates of metals. The probable chemical mechanism and action of corrosion inhibitors have been extensively investigated. Inhibitors have been discovered empirically and are tested under conditions similar to their proposed industrial application. The inhibitors were then investigated further to measure and if possible to explain their inhibiting effects on the corrosion rate (Yang, 2021). Inhibitors are usually species that modify the reactions or suppress the local galvanic action in galvanically coupled electroactive elements. Inhibitors are rarely used in drinking or edible water as either passive corrosion inhibitors or cathodic corrosion inhibitors, although some water purification systems do use cathodic/anodic corrosion inhibitors with limited success in corrosion inhibition. This problem has led to the use of effective corrosion inhibitors, but often in relatively high concentrations which can prove toxic and are not satisfactory environmentally friendly inhibitors. Organic inhibitors based on plant extracts have become increasingly used, particularly in the last two decades. They appear biocompatible and possess good corrosion inhibiting properties against steel in aggressive water and saline media. However, many of the organizational and industrial inhibitors are, unfortunately, also toxic and carcinogenic.

New environmentally friendly green corrosion inhibitors are required for metals, metal alloys, their coatings, hybrid coatings and for the passive corrosion inhibition of alloys. This is particularly relevant for the tank construction, production, transport and storage of edible oils which are currently inhibited using toxic synthetic corrosion inhibitors at potentially carcinogenic concentrations. Green inhibitors based on polyphenols from olive leaves, rosemary, red clover, pomegranate peels, sweet gum trees etc. were prepared for different metals, metal alloys and over coatings. These leave extracts functioned as efficient green corrosion inhibitors in aggressive water and saline media in reducing the corrosion rate of the metals, notably steels and some copper alloys. The natural extracts were cheap, biorenewable, biocompatible and biodegradable. They exhibited up to 99 % inhibition efficiency even at concentrations lower than 10 ppm. They were able to passivate alloy anodes and protect against pitting corrosion. Hybrid bionanocomposite coatings based on quercetin and polyphenols from plant extracts containing different clays were prepared on aluminum alloy. These coatings inhibited corrosion and stress corrosion cracking.

II.7. Structural analysis

Corrosion is a natural process of deterioration of metallic materials that occurs through a sequence of electrochemical reactions with the environment. From the structural point of view, the effect of corrosion is a gradual thinning of the materials cross sections, leading to a loss of the resistant areas and, therefore, to a decrease of structural performances. The progressive damage mechanism produced by corrosion is similar but different from the one caused for other deterioration mechanisms, such as fatiguing, for instance. Several studies are available in scientific literature on the design of structures against these phenomena, analysing the evolution of this damage and proposing a prognosis of the residual life in terms of structural performance. The adoption of these design procedures requires the availability of a thorough description of the damage, but more importantly, the distinguishing parameters controlling the damage mechanism, still being simple and robust.

For corrosion, it is limited to say which were the major design criteria for analysing or predicting the corrosion related failures. The focus will be to show what the main design criterions are, leading to a new set of identifying parameters controlling the corrosion mechanism, able to define simpler and more robust criteria than the current ones. Then description of how difficult it is to define a procedure against corrosion that can be accepted and implemented by current designers. Descriptions will also highlight why corrosion design procedures are currently not followed in practice, and simple messages that would be appropriate to get across to designers in practice, to convince them to adopt these procedures.

The probabilistic model of corrosion based on time-variant corrosion rates (Cascini et al., 2014) is presented and validation results are reported. The paper also comments on how designers could make use of the model in analyzing corrosion risk. Environmental factors affecting the exposure of steel structures to atmospheric corrosion can be reduced to two parameters based on the determination of the site atmosphere corrosivity. Corrosion rates under well-defined conditions of temperature and humidity are available from empirical formulas and models. The predicted corrosion variation under different environmental conditions needs to be calibrated working with local climatic conditions. Moreover it highlights how crucial is the availability of rigorous and reliable corrosion data and commented on possible further developments to collect data from practitioners.

II.7.1. Load considerations

Corrosion is a wearing away of metals by a reaction with their environment. This deterioration process can be defined as a random process because of the inevitable uncertainty of the concerned parameters such as environmental parameters, mechanical stresses acting on the structure, material properties and corrosion progression rates. Structural deterioration due to loss of cross-section caused by corrosion has been accepted as a very important topic in the analysis of aging structures. Steel structures with thin-walled members that are exposed to atmospheric corrosion take a high risk of corrosion because of poor access to the surfaces for visual inspection and maintenance. The control of structural performance based on probabilistically predicted corrosion rates is one of the challenging topics in this research field (Cascini et al., 2014). Recently, a generic and flexible method for time-variant advanced reliability analysis of thin-walled framing systems of arbitrary topology was developed. In addition to the development of modeling, appropriate input parameters must also be prepared. In particular, the estimation of the initial corrosion rates and the statistical parameters for the probabilistic spectral approach are non-trivial tasks. A method for estimating a deterioration model of atmospheric corrosion applicable to Tokyo Bay was suggested. In the suggested method, the probability that the corrosion rate becomes a certain value during the predicted time is calculated based on the environmental parameters such as temperature and humidity, and the cumulative frequency distribution of the corrosion rates is obtained. Several developed probabilistic deterioration models which can be applied for future prediction were also presented. These types of studies were carried out in accordance with climate, but there has been little consideration of modeling on atmospheric corrosion based on the differences of corrosion types.

The modeling of atmospheric corrosion is complicated because the corrosion process has a very complex nature which varies depending on the types of corrosion. In atmospheric corrosion, corrosion of steel in carbonated environments precipitates uniform rusting, and the corrosion occurs beneath a layer of mud drop, and galvanic corrosion occurs at the junction of different metals. Atmospheric corrosion has time-variant characteristics and induces time-variant structural performance due to variations in environmental parameters. Consequently, breakpoint models with user-defined distributions were presented for cumulative temperature and humidity parameters in modeling time-variant environmental conditions. Atmospheric corrosion rates also take a range of values, and this is a widely accepted reason for representing time-variant corrosion rates with a probability distribution function. Parameter distribution of the developed deterioration model was fitted to one of the widely-used statistical survival distributions, four-parameter log-normal distributions, employing the curve fitting toolbox of a statistical software.

II.7.2. Failure modes

First of all, structural failure modes are explicitly described and illustrated. In this research, the safety and stability of in-walls structural system against corrosion attack is to be assessed. As commonly accepted, a review of corrosion hazard classes and corrosive environments is first provided. Reinforcement steel corrosion modes are underlined and approaches to assessing the consequences of corrosion in terms of the estimated loss of safe performance levels are considered. Basic principles of service life prediction of corrodible structures against atmospheric corrosion notably the probability of corrosion initiation and time to local removal of protective treatment are briefly outlined. Modes of corrosion-related accidental structural and structural element failure are summarised and illustrated along with corresponding reliability assessment conceptually illustrated. Recent safety assessment studies are reviewed. The shortcomings of existing approaches to the safety assessment of steel in-walls systems in terms of failure hazardous feature sets indicated by recent research are discussed.

Structural failure modes are, depending on a number of factors, harmful influences, character of stresses, material condition, nature of loading, type of structure and execution technology, dominantly classified as shown in figure 2.2. They can be put into three classes: a) accidental failure modes, b) failure modes related to corrosion and fire and c) failure modes not related to corrosion and fire loading. Accident-related modes include progressive failure modes, modes related to shock and impact loads, overload modes, explosive failure modes etc. Fire-related modes include all types of failure modes which are caused by fire loading or which are initiated by fire loading. Modes of corrosion-related accidental failure have been researched in detail during the last three decades (Cascini et al., 2014). A number of corrosion modes specific to concrete steel reinforcement failure or loss of serviceability of structures and structural elements are grouped into four main classes: a) extensive concrete cracking, b) local corrosion with material loss of active part, c) loss of bond between rebar and concrete cover, d) other modes. Possible consequences of local removal of protective treatment and resulting atmospheric corrosion of internal steel structures typically include: a) working failure modes, b) loss of stability failing modes, c) dynamic stability failure modes, d) local corrosion-related capacity loss modes. The illustration of possible corrosion-related failure modes of IRC-G-ER in-walls steel structures to be assessed against corrosive environment is shown in graphic.

II.8. Case studies

New generation Corrosion Resistance Structures (CRS) in the demanding market should embrace a new perspective in design: The structures should resist corrosion from the base design, and not during the next maintenance action. From the corrosion-chemical point of view, to resist corrosion is different to be protected by corrosion. A CRS should not rely on reactive materials or corrective actions. Designing a structure being corrosion resistance includes performance concepts that are new for most structural engineers and their codes.

Today, the Structural Engineers fight a war against corrosion, trying to provide the necessary structures that will be built without solution of continuity in high saline marine environments. The game is very asymmetrical, where the Designer has always the worst part, due to the design versus life of the structure limitations. The material, the corrosion potential, whatever it is, does not have limitations.

High saline chlorides, that produce a ten times higher pH leveling down in water, together with highly permeable materials like concrete blocks, is the “perfect storm” leading for corrosion to form and grow. The present creative concept is based on pure analytical concepts from the designer’s point of view with applications on high saline conditions. The corrosion resistance/affectivity threshold if from either from materials perspectives gives wide limits for investigating ultra high performance materials, yet with duration and questions.

Structural Engineers design demanding exacting lightweight, large span structures constantly exposed to the elements on the coastlines. Nevertheless, these environments present harsh conditions because of the corrosive nature of saltwater and salt spray, while saline structures are indispensable worldwide. Corrosion is usually treated as a failure problem. First world coastlines rich in corrosion marine pollution leave structures unguarded. The pre-stressed concrete bridges, urban flyovers, building roofs, decks, are all exposed currently in the reclamation process casualties losses. Heavy documents, moving, rotating, vibrating, safety loads, lighting, all vital but corrosion motion evading monitors process of ebbing and not.

It is desirable to enable adoption of the designs for resisting marine corrosion as needed specifications. Typical members of new generation low maintenance structures are concrete used in marine construction sites. A full time analysis is burdensome for the performance here reviewed elements yielding a semi-lagrangian equation of motion. Code value calculations yield contingent input values. Members diameters exhibiting sea use are requested. Because the intensity magnitude interval coverage is 30dB orders, regulation requirements questions necessitate re-elaborate input.

II.8.1. Bridges

Bridges must be designed for structural strength, stability, and functionality, as well as anticipated anti-corrosive properties. Even though the designer's job is to create corrosion-resistant structures, there are factors that cannot be predicted. These include the corrosive environment, the actual traffic load, the structure's reaction under load, and subsequent modifications to the structure (Gocál and Odrobiňák, 2020). In the case of severe corrosion, the life of the structure may be shortened even before the design standard has been achieved. In such cases, it becomes apparent that the structure does not meet the expectations of the designer, in terms of stability, strength, and functionality. Although bridges that meet the design standards can be subject to rigorous and desirable inspection and maintenance regimes, such structures may still reach an emergency state because of unforeseen deterioration or failures.

Cars and trucks crossing a bridge exert lateral and vertical reactions that act in the span and bearings. These reactions are distributed in accordance with the construction in the longitudinal and lateral directions. This distribution is usually more complex in a real girder bridge. In the case of a highway bridge, for example, if the geometry of the cross-section, material parameters, and load are uniform, the torsional stiffness is usually higher than the lateral stiffness. If out-of-lane loading occurs, some of the cross-section is subjected to greater stresses than anticipated (R. Kayser and S. Nowak, 1989). However, not only when the design load exceeds the designed load did any unforeseen deterioration occur. Localized corrosion of the cross-section over a specific length and depth may also cause invalidity.

II.8.2. Marine structures

Corrosion is one of the worst causes of damage to marinas and marine structures. Corrosion pits cause local stress concentrations that reduce the fatigue limit of a stressed structure, leading to brittle mechanical failures. Corrosion in wave impact zones leads to premature structural failure. Protective measures can include coatings, cathodic protection, design choices, inspection, and maintenance (Kyun Kim et al., 2014). Some examples of marine structures include jetties, buoys, breakwaters, piers, and docks.

Coating and applying paints can be the least costly measures added during the preparation or construction phase. Paints protect structures by smoothing surfaces and making them non-wettable with water. Paints are made of resins, pigments, solvents, and additives. Resins make up the bulk of paint and are polymers that adhere to substrates and seal from wetting. Pigments provide color, some specific functions, and protect coatings from ultraviolet radiation or damage. Solvents thin down viscous paints to make them flow into crevices during application. Additives improve the composition's performance, stability, or ease of application. Mono-component paints dry by cross-linking and toughening resins. Bi-components must be mixed before application.

Paints can last five years on well-maintained structures and less on those in harsh weather-exposed conditions. Unbelievably, no coatings can prevent corrosion indefinitely. At present, in-situ paints cannot be repaired directly, and several layers must be stripped down periodically to access old paints and bare steel. On top of this, paints are cheap, biodegradable, and safe for small mammals. They also fail on the structure health-monitoring scale and can no longer be economically measured for flow coating or fragility with invasive stamps.

II.8.3. Industrial facilities

Corrosion damages almost all types of structures and construction materials in various climates, environmental conditions, and exposure. The corrosion damage of structural materials directly results in serious safety and economic issues occurring. In industrial facilities, the inspection and maintenance of protective coatings, tough, durable, and corrosion-resistant materials play vital roles for controlling corrosion. For vessels and piping systems, their exposure means to be fully covered in fluids containing various chemicals at various levels of pH value and temperature. A lot of corrosion-resistant materials, such as high-alloyed steels, plastics, and glassfiber reinforced plastics, are used. Other structures like buildings and steel frameworks with surface treatments and coated, also require inspection and maintenance of exterior finishing. Visible corrosion on structures generally indicates the problem, but the effects of corrosion on the structural member's load-carrying capacity/buckling stability cannot be detected beforehand until failure events occur (Cascini et al., 2014). Guidelines for inspection frequencies and conditions proposed by existing codes and standards are not sufficient to forecast failure events caused by corrosion. Long-term mechanistic/analytical time-variant methods for corrosion assessment are needed.

The base of atmospheric corrosion models proposed by the last few decades has been summed and classified as a semi-empirical Eyring-like or a mechanistic diffusion model. The latter needs meteorological inputs, but the former can significantly simplify modeling procedures at the national scale, which will make their popularity increase in the future. Various corrosion maps built upon climatological parameters are originally worldwide semi-empirical electrochemical models. Field observations indicate that de-icing salt use causes aggressive atmospheric corrosion in a wide area. Various databases and mathematical methods have been employed to predict the locations of the structures as well as the traffic density, temperatures, road slope, and de-icing salt use through the field survey in Sweden. A timetable for expert observation campaigns has been automatically preplanned (Rzeszut et al., 2016). Deficiency and reduction ideas planned in maintenance management must complement data and safety requirement analyses. The major goal of long- and short-term maintenance management is to make and execute the maintenance management plan that achieves necessary safety requirements at minimal total long-term cost over the analysis period. By using a novel approach implementing the U-shaped service life functions, the total cycle cost of long-term management in greater industries has been quantified. Cost estimation models for preventive maintenance and repair work of minor damage were proposed.

II.9. Testing and inspection methods

Testing of Corrosion Risks. The choice of parameters for corrosion testing depends on the objective of the test. For instance, testing material resistance to corrosion should involve using standard test methods, and the results must be reproducible and include physical phenomena that would disrupt the corrosion barrier with time. Selecting accelerators such as salts, surfactants, and temperatures is crucial to speed up the results of material resistant tests. However, the corrosivity of the agent should remain representative of the corrosivity prediction in the service environment to support the coatings' M. A. objectives. Alternatively, exposing materials coated with different systems to real service conditions and routinely assessing the system's appearance, thickness, and M.I. can be used for nationwide structural reliability assessments.

To mimic the other corrosion mechanisms such as CRC, the test approach needs to be designed with regard to the environmental aggressiveness and physiological parameters as well as the performance criteria. In addition to that, unexpected changes of some key aggressiveness can be scanned through utilizing synthetic ocean water. For evaluating M. A. of designs or systems, approaches should incorporate database methodologies to assess spatially and temporally exhaustive results, for which the standard M. A. thresholds should remain effective (Adel Al-Kaseasbeh, 2015).

Periodical Inspection and Definition of Mechanisms. The target structures should be inspected periodically throughout their lifespan. However, the initial estimation of the inspection frequency remains a crucial task for all the parties in a steel structure project. The frequency should balance the construction cost and the benefit of the inspection. Compared to a well-established determination of standard inspection frequencies for common bridge geometries and environments, it remains an open question for more innovative structures.

Another critical question for nationwide integrity and for those requesting more service information on structural systems is the definition of the damaging mechanism(s) behind an early inspection report.

Much literature has been published about bridge inspection and damage definition. However, as for those complex mechanical structures, their novel inspection and integrity assertion are still unrealized and even cannot be set forth in the literature. A top-down approach should apply M. R. detection and PIC to provide nationwide inspection values.

II.9.1. Visual inspection

Visual inspection is one of the oldest means of assessing structures. The officer responsible for inspecting any structure can detect most problems virtually 'at a glance,' and will immediately act accordingly. This greatly reduces the cost of regular inspections and often eliminates any need for more sophisticated methods afterwards. Each person tasked with this must gain experience, however, as novices in any field are often unaware of what to pursue, or simply ignore some problems simply because it takes patience and time to analyze each structure thoroughly.

Visual inspections involve the naked eye and/or mechanical aides. In many cases, visual inspection by the naked eye is sufficient: experienced personnel can identify problems before the situation worsens. In some cases, however, using an airplane, helicopter, or drone mounted with a video camera is essential. These can capture the state of a structure, and offer that footage to a human operator recognizing the problems. These aids have proven effective at managing large structures, such as overhead truss bridges, railway bridges, and stadiums, in some countries (Iron and Steel Institute, 1970).

Visual inspection devices and methods can be classified into three levels: screening, inspection and assessment. Screening level visual inspection devices are typically simple and can often be used in isolation. They are mainly intended for short visits to the site; the information they collect will instruct the owner how to carefully manage monitoring efforts.

Inspection level methods provide more rigorous assessments, but are also more sophisticated and expensive. Damage identification, such as crack detection and shape detection, is often pursued, as are structural verification and health monitoring. Most devices at this level involve a human cognitive process as well, and many different kinds of devices and support methods fall into this category. In some structured inspections and assessments, hand-held devices such as infrared cameras and acoustic imagers are employed. They usually cost tens to hundreds of thousands of US dollars. In such cases, the owner often hires professionals or specialized external organizations.

Assessment level visual inspection methods typically include the same purposes as inspection level ones, but are more sophisticated. Actual structural modifications, such as the use of control agents, moving or cutting materials, or adding parts, are typically adopted at this level. Considerably more complex calculations are often done to examine these effects. Discrete elements methods (DEMs) and computational fluid dynamics (CFDs) have been commonly used for assessment level analyses. These are often executed in cooperation with the inspection level methods.

II.9.2. Non-testructive testing

Testing by non-destructive testing methods must be performed at specified intervals after executing the corrosion-resistant structure. It should be a design condition to put corrosion sensors or measurement modules at weak or vulnerable locations in the corrosion-resistant protection structure. These locations include: 1. Dangerous or Controversial Coated Area. Usually, this area is a new pipe section where the coating layer may not have a tight interface with the pipe underground. It can cause the DCP to change from old condition to new condition in a very short time. Therefore, quick NDI/E as a checkup task of construction quality is desired. 2. Deteriorated Weld Joint Area: The coating and protection of the weld joint connection usually has the following defects: connector head exposed at the ground surface; pipe joint is not coated properly or is peeled back; improper coalescence welding causing rusted spots on the steel pipe; and missed paint application spots and coats over-coating. 3. Neutral Ground Area: In a neutral-ground area, the pipe is sensitive to stray current due to its low ground potential. Non-destructive testing is very important to ensure corrosion protection is being maintained in this area. 4. Un-Monitored Anomaly Area: In a few places of long pipelines, the operator’s cathode protection criteria cannot be reached. In some extreme cases, the voltage gradient can be above 300 mV/m. These faulty areas can be monitored by extra sensors.

II.9.3. Corrosion rate measurement

The rapid proliferation and development of electrochemical methods, as well as sensor and computing technologies, are expected to enable effective corrosion monitoring during the early stages of infrastructure use. An electrochemical approach to detecting and monitoring the corrosion of embedded steel rebar bridges on the Korean highway roads. It develops a prototype, conduct field tests, and validate reliability while aiming at commercial introduction. A full system operation test on this prototype showed unchanged reliability over a monitoring period of 37 months. The specific design concept, methods, and field test results will be introduced.

Almost all civil structures are constructed of concrete. One of the key materials used in concrete structures is steel rebar, which enhances the tensile strength of concrete. But corrosion of exposed steel rebar can induce serious damages to concrete structures, so special care should be taken for the durability of the rebar. To protect from corrosion, firstly a layer of rust-preventive agent is usually applied to the rebar surface. This film allows long-life durability but should be monitored. However, existing physical methods for field tests are very inefficient because the approach often requires labor-intensive work and the detection occurs manually at a small scale. Furthermore, the existing methods are often indirect measurement without proof. After the construction of concrete structures, it is generally impractical to measure coating thickness variation to predict the corrosion risk.

In response to this need, the research develops a wireless passively interrogated sensor using a piezoresistive-type flexible interdigitated capacitor structure. It describes the feasibility study for a sensor and the crucial steps before prototype testing and their results. The sensors are verified under thermal deformation and humidity environment conditions showing stable operation. The research aims to develop an ultra-long linear actuator that can be embedded into thin concrete structures, operated by an electromechanical principle, and monitored by a passively interrogated wireless passive sensor. The operation performance of the actuator is verified according to excitation frequency, resonance frequency, and maximum deflection while considering the safety of concrete thickness. The sensor is proven to be effective through static bending tests.

II.9.3.1. Regulatory standards and guidelines

Regulatory standards and guidelines allow to verify the correctness of the completed projects and implementation of a cheaper solution in relation to a conventional form. Solutions provided in design codes and guidelines remove the doubts regarding the selection of analysis methods or assessment criteria, which are discussed on the basis of scientific studies and experience. They are conventionally international so they streamline the same basic knowledge regarding design of corrosion-resistant structures. With regard to elements made of reinforced concrete these are commonly used codes and standards, which are mentioned below.

The code specifies the materials, strength of concrete and steel, solving the equilibrium condition of structures, design of elements, detailing of reinforcement, reinforcement ratios, creep and shortening of a structure, buckling of compression members, effects of temperature and shrinkage, alternative scheme of verification of structure stability, fundamentals of field measurements, inspection of steel and concrete structure, concrete work acceptance, information on control test and measurements, advantages in precast structures.

The codes state requirements for the design of concrete structures, including limit states and their provisions regarding matters to be considered in the verification, durabilities, and exposure classes, inherent material characteristics, structural analysis and assumptions, a simplified approach using a combination of analysis methods, design rules for structural elements, stability of structures, detailing of reinforcement, operational factors, deflection and crack control, section resistance for punched shear, structural design and detailing in accordance with a non-linear analysis, foundations, including dimensional tolerances, responsibility of structural engineers, requirements for a design report.

This code regulates the minimum requirements for the design, materials and detailing of structural units serving predominantly environmental engineering purposes. Regarding design, equations on strength criteria, as well as permeability, are stated. Buckling analysis of wall panels on the basis of 2D shell elements and commercially available software is described. Analysis of behavior of reinforced concrete walls with various ratios of longitudinal reinforcement in DBE, DBE+E and DBE+E+SE load combinations is presented. Content of the code is collected on the basis of review of design specification and published research works in the scientific journals (Rzeszut et al., 2016).

II.10.1. International standards

Corrosion is a process and mechanism that occurs as a result of the interaction of a material with the medium in which they exist. It leads to changes in features that cause irreversible damage to a structure, as a result of which its initial load-bearing capacity is reduced or lost, leading to failure. Corrosion affects both natural and manufactured materials. Society’s progress is heavily dependent on the development of new materials, including those used for structural purposes. Nevertheless, each material has its own limitations. In most cases, a designer’s first choice will be concrete or steel; however, there are also materials that are more resistant to aggressive corrosion conditions but are not commonly used in load-bearing structures. Alternative materials are gaining importance and become more common in engineering calculations, as evidenced and illustrated by numerous practical examples.

In loads-bearing structures in aggressive corrosion conditions, aside from concrete and timber as alternative non-corrosive materials, corrosion-resistant steel and aluminum alloys may be used (Rzeszut et al., 2016). The use of stainless steel for the construction of elements exposed to the corrosive effects of the environment, together with already existing corrosion aggression, is still limited. An important aspect is the often-high costs of such materials compared with conventional structural steels. The varying content of alloying elements (chromium, nickel, molybdenum, nitrogen, copper, etc.) in various grades (0.2% and even above) and stainless-steel products (rolled, forged, cast, etc.) contribute to significantly varying susceptibility to corrosion. Designers must keep in mind the first-grade construction (general application – austenitic steels) being more corrosion resistant in contact with steel (Arrayago Luquin et al., 2022). Anodized/untreated aluminum shear connectors must not be used, particularly with reinforced concrete structures.

Unfortunately, bent elements made of high-strength non-corrosive alloy steel do not currently have a standard design approach. Too few research papers have assessed the structural design of such elements, particularly those in which loading simultaneously exerts tensile and compressive forces. Unlike stainless steel, on which strength and stability standards are being developed, information on the structural design of such elements is confined to a short note in American codes, which do not include standard notes and equations.

II.10.2. Local regulations

Corrosion is a significant durability factor for steel structures, particularly in aggressive environments, where material degradation may be quite rapid (Cascini et al., 2014). In recent years, the corrosion design of steel structures has drawn many researchers' attention, leading to numerous analytical studies and modification of National Design Codes. Nevertheless, some aspects need to be improved: in many National Codes, corrosion is just featured in the local regulations while no internationally agreed empirical or semi-probabilistic model is available. Therefore, the safety level of corrosion resistant structures in one Country is not comparable with the safety level in another Country that has adopted a different corrosion design philosophy. Given the evidence that corrosion may not only attack and degrade the functionalities of structural members, but also change their cross-section shape permanently or increase the levels of internal stresses in coatings, reducing eventually the time between failures and maintenance operations, some design recommendations and procedural guidelines to assess lifetime performances and loading conditions should be required. Management agencies are asked to mitigate the physical hazard and ensure sustainable investments performance to preserve its long-term usability and safety. Amongst the possible adversities that may affect it, corrosive phenomena play a crucial role from the maintenance and preservation point of view: in fact, corrosion seriously damages the structures and makes them unsafe. It is consequently of interest to define a detailed methodology to assess the corrosion performance of a structure in the specific environment where it has been built. Such a methodology may provide diagnostic tools to recognize closely the aggressiveness of the environment, type of coatings or protective measures implicated, likelihood of failure, main loss of performance parameters and evolution laws. The relevant Statistical and Probabilistic Design Model involve in a coherent framework the likely forecasted scenario taking into account the available information at the moment of inspection.

CHAPTER III

CHOICE OF MATERIALS FOR CORROSION PROTECTION

Chapter III : Choice of materials for corrosion protection

III.1. Material selection criteria

The selection of materials for corrosion protection purposes is determined by a set of alternative selection methodology, an introduction to this set using clustering comparative importance method (CCIM) in decision-making to material selection for corrosion protection purposes, and the presentation of severe test cases. There should be material selection criteria for corrosion protection coatings on metallic substrates to enable the selection of optimal coatings at the early stage of product development. In order to provide alternative material selection criteria for corrosion protection, procedure for screening materials using decision-making method is developed, which consists of MAUT, rough set analysis, CCIM and fuzzy inference. A set of corrosion protection coating screening procedure is presented to enable the precise selection of coating to be evaluated further (Gong et al., 2024).

The material coating selection criteria are a set of alternatives screening means. The mechanics of corrosion protection and why exothermic formulation is selected as screening option are also discussed. Using a set of initial material selection criteria for corrosion protection and in the absence of commercial implementation (currently the best nominated alternative), this initial screening procedure is suggested for use as guide either independently or with group decision-making. This selection technology is easy to implement and suitable for both group and individual decision-making (Harris et al., 2019).

Inadequate coating adhesion should be considered as a selection criterion for corrosion protection coating. This topic is described in another paper. This additional selection criteria provides groups with the option of panel-occurrence scores to narrow down coating candidates. Coating thickness is an additional screening selection criteria. This criterion is well addressed in other papers. It identifies which coated materials are unprotected against corrosion. The presented material selection criteria are general so that they can also be applied to self-repairing coatings for corrosion protection which are discussed in a separate paper. It is important that available material selection criteria are promulgated.

III.2. Corrosion resistance

Corrosion of materials in an atmosphere increases with rising humidity and temperature, the most widespread protection for equipment and buildings in these conditions being metallic. Prior to galvanizing, metals are covered with a coat of dross, i.e. a mixture of oxide, chicory and burnt material. The former does not adhere, and after the coating has been removed, the metallic surface can be immediately galvanized with no further pretreatment. High security applications. The work presented here constitutes a study of the application of thermal spray and subsequent heat treatment on the galvanic anticorrosive capability of aluminum on both stainless steel and carbon steel (Dror Bergman, 1996).

Galvanizing AG 320–350 gm/m2 is either thermal sprayed or coated with 93Al/7 Zn metallisation prior to heating at 520° for 5 h in argon. Electrolytic long-term corrosion tests in H2S, NaCL+28 H2O, and Na2S+72H2O solutions in stagnant and flow conditions show that heating alters the corrosion mechanism of aluminum, the extent of which is dependent upon the starting microstructure. Al aluminum coating. High temperature heat treatment turned the majority of the aluminum of the heat treated specimen into triple layer aluminosilicates, with the rest possibly comprising a continuous layer of aluminum oxide incorporated within the aluminosilicate network. The interdiffusion and the reactions with the thermal expansion of each of the coating materials leads to a large change in the coating morphology, which in turn influences the water uptake of the coating and hence the long-term performance. Analytical transmission electron microscopy has indicated that the thermal spray coating contains sub-10 nm protrusions, which are believed to serve as nucleation sites for the growth of the fibrils which form an intricate three dimensional interconnect network.

The equiaxed porosity of the gel coating is thought to increase its resistance to breakdown, possibly because of the lower tensile stress resulting from a lower strain gradient in the porous coating. Again, suggested explanations include the rapid coalescence of slightly polymerised droplets into a network of fibrils and slower densification of compacted glasses, leading to a near quit layer intermediate in resistance between the continuous and foamed types of glass. Overall, both types of coating benefit from a process of rapid dehydration, probably involving deprotonation, which converts the initial light brown coating into a crack free dense layer.

III.3. Mechanical strength

Designing durable materials for building construction involves considerations of functional, practical, technical, and economic characteristics of the materials. The functional characteristics are directly linked with the expected service life of the building and the final aesthetic appearance. Almost all materials, whether in the form of stone, concrete, wood, glass, or metals, are subjected to types of degradation processes affecting their structural integrity and aesthetic appearance throughout their service life. Analyzing and understanding ongoing degradation processes for buildings is very complex because construction materials often experience numerous degradation processes simultaneously. Knowledge of the specific degradation processes affecting individual materials is essential in developing integrated conservation plans for whole buildings or building complexes. Therefore, design and capitalization of protection systems against corrosion are desperately needed, but should rely on profound knowledge and understanding of the corrosion processes and protecting materials (Li et al., 2022).

Such knowledge should also be supported by long-term monitoring of the degradation processes at the material–environment interface by non-invasive inspection techniques. Therefore, there is a great need for affordable and simple instrumental techniques allowing long-term monitoring of the corrosion processes affecting historical and modern buildings. A variety of classical electrochemical techniques for monitoring corrosion by using metallic sensors were discussed and new promising electrochemical techniques will be presented including self-regulated electrochemical sensors for monitoring corrosion in continuous on-line mode.

The combination of metallic corrosion but also chemical degradation processes affecting the electrochemical behavior of the monitored metals will be discussed. Furthermore, the development of advanced sensors for the in situ monitoring of the service-life of traditional and innovative corrosion protecting systems will be presented. Finally, a vision for the further improvement of the sustainability of our building infrastructure by developing composite sensor–protecting systems will conclude the discussion.

III.4. Cost efficiency

Cost efficiency is another important criteria. It affects the material selection and its application strategy. The cost of materials is often the first thing that facility managers want to know. The use of low-cost materials, even when they are not the best choice from a performance standpoint, can lead to serious criticisms from upper management, damage to a company's reputation, and possibly even criminal prosecutions in the event of catastrophic equipment failures. Facility managers are often aggressively challenged to find unique ways to protect vulnerable equipment. Therefore, there are frequently underfunded or neglected areas that present an opportunity for gains in equipment reliability with repair or upgrade expenditures (Chowwanonthapunya et al., 2016).

Cost-efficiency selection criteria can be very difficult to define objectively because economic considerations are typically politicized and associated with many subjective attributes. The determinants of cost efficiency include the initial material cost, delivery time, installation cost, insurance, maintenance, decommissioning, salvage value, remaining use-life of the protection devices, tax ramifications, and penalties for equipment failures. Outwardly, the objective differential cost-component determination can be accomplished using workshop and/or management methods. Unfortunately, results can be argued based on cascade effects and inopportune assumptions included in the analysis. The drawbacks of these techniques cause cost-efficiency decisions to be among the least satisfactory, especially in an environment where many alternatives are being considered.

A current practice that appears to circumvent some of the difficulties in defining cost efficiency is a "multiple selection criteria analysis." This analysis is performed using graphical curve-fit procedures combined with estimates for the uncertainty in adjusting the criteria (including cost). It can be an effective preliminary tool for technology screening so that more independent measurements of the cost criteria can be developed. Nevertheless, un-objective canvassing and sophistry is sometimes used to filter responses. Even in the absence of subterfuge, when a particular technology wins, the consequence can be mistrust concerning the validity of the decision-making analysis.

III.5. Availability

Many different kinds of coatings for corrosion protection are commercially available, and new systems are keenly awaited, especially those based on new concepts such as switched corrosion protection using Smart Coatings, bio-inspired coatings and coral-derived materials, anti-biofouling coatings with frictional and toxic principles. However, most of these potential new coatings have their shortcomings, either with respect to their inherent efficiency to protect against corrosion or their safety in service, with respect to both the environment and human health; a concept that relates to 'sustainability' is still a challenge, especially for surface treatments and coatings for metals and alloys. Therefore, finding suitable coatings for corrosion protection of metals and alloys that is effective and sustainable is a scientific and technological challenge, also for academics and researchers in coatings science and technology and its applications as well as for industrial actors who develop, manufacture, and apply surfaces for metals and alloys. Especially those responsible for R&D, Product Development and Product Engineering, as well as scientists of research institutions, universities, and high schools with focus on coating science, paint technology, surface treatment and related fields, are the potential distributors of and acting scientist-researcher in such a meeting venue (Sukanya et al., 2022).

III.6. Common materials for corrosion protection

Protective coatings are often made of organic polymers, silica sol, silicate, borate, phosphates, metal phosphides, or oxide based nanomaterials and polymer composites (Ammar et al., 2018). Metal oxide coating such as Al2O3, TiO2 and their composite with polymers is a widespread method of protecting metals from corrosion (Uddin Ammar et al., 2018). Generally, metal alumina or polystyrene coatings alone could provide improved corrosion protection. However, due to their high porosity, the coatings were less effective in the long term. While with the incorporation of GO into PS coating, the corrosion protection performance increased significantly indicating the potential of the composite coating for long-term protection of metals against corrosion.

Some electrochemical studies confirmed the high efficacy of protective coatings such as carbon steel-based polymeric nanocomposite coatings in providing corrosion protection. However, an effective long-term coating should combine several strategies such as anti-corrosion and anti-biofouling mechanisms in a single coating which have never been realized. Incorporating hydrophilic polymer or silicate sol in currently used superhydrophobic coatings would be beneficial to improve their long term stability. Silicon-based nano-coatings are emerging coating materials due to their non-toxic and high-performance material. The incorporation of cerium salts could further increase corrosion protection which needs to be further studied. Carbon materials with hydrophilicity or anti-biofouling ability could be incorporated into protective coatings for better anti-corrosion and anti-biofouling performance.

Cathodic protection is a different corrosion protection mechanism compared to the previously mentioned coatings. This technique is mainly used for underground pipelines and tanks where a sizeable electrochemical probe is placed near the work. It then reduces the corrosion rate but does not eliminate it. This method is less used in offshore environments. Additionally, any related system will lead to a much larger price than a commonly used coating protection. Therefore, this text mainly concentrated on inquiries related to the coating and surface pretreatment of metallic structures.

III.6.1. Stainless steel

III.6.1.1. Types, designation, and strength of stainless steel

Stainless steels are classified mainly into three categories: ferritic, martensitic, and austenitic steels. Ferritic steels contain chromium as the main alloying element, and martensitic steels are alloyed with chromium and carbon. Depending on the heat treatment, the microstructure of austenitic stainless steels changes from austenite to martensite or retained austenite. To prevent the phase change to martensite when subjected to welding and heat treatment, ferritic steels are mostly used for un-welded oil and gas applications. Out of all types, only austenitic steels are used for welded applications because welding causes severe oxidation of the base metal in the heat-affected zone (HAZ). Hence, for welded fabrication of oil and gas applications, only austenitic stainless steels, such as grades 304 and 316, are used. Grade 304 is a low-cost, general-purpose material for boiled water and food applications. Because of low carbon content, type 304-L does not intergranularly corrode by the sensitization mechanism (Dror Bergman, 1996).

III.6.1.2. Selection of stainless steel

Stainless steels have excellent properties such as high strength-to-weight ratio, corrosion resistance at elevated temperatures, thermal fatigue resistance, low thermal expansion coefficient, and good machinability and weldability, for structures in saline ocean-going vessels, desert, and chemical application environments. A strict specification of materials beforehand will prevent cracks, de-lamination, and blistering during the application stage. Therefore, selection of these steels and rigorous surface preparation procedures before application is crucial.

III.6.2. Aluminum alloys

Aluminum alloys are classified in several series depending on aluminum alloying agents; 1xxx, 2xxx, 3xxx, 4xxx, 5xxx, 6xxx, 7xxx, and 8xxx series. Aluminum alloys of 2xxx series which are grouped into Al-Cu system, known as AA2024 alloy, have enhanced specific strength which make them be the first choice for aerospace industries. This aluminum alloy has excellent strength to weight ratio and fatigue resistance. Unfortunately, aluminum alloy AA2024 is known with their poor corrosion resistance, therefore it requires surface treatment to protect the metal against the attack of aggressive species (GANAPATHY et al., 2018).

Defect like micro rollers on the surface of aluminum alloy AA2024 strongly influence the adsorption of coating and are the sources of corrosion. Due to its micro porous, ZrO2 has been widely used as a barrier coating as it has very low permeability properties. Among the initiation mechanism processes in the coatings, pitting is the most destructive type of localized corrosion in Al alloys. So the growth of another pit may or may not be the result of the corrosion cycles of these preexisting pits.

Corrosion is a natural phenomenon that can attack metals and alloys when its exposed to corrosive media in the environment. In corrosion, metals lose electrons forming ions. Corrosion also has a detrimental effect on metals and alloys. Therefore, the corrosion needs to be prevented.

There are some ways to prevent corrosion such as using corrosion inhibitors, coating with impervious and non porous materials, and using a sacrificial anode for cathodic protection. Corrosion protection by coating is one of the best ways to cover metals against corrosion by passing the attack of corrosive anions and ions. Several ferrous and non ferrous metals have used either physical/organic or inorganic/metallic coating.

III.6.3. Copper alloys

Copper alloys have a variety of marine applications for which they are anticipated to provide significant service life. Most of these applications involve protection to be provided by a copper alloy, which form a substitute for iron based alloys, the effectiveness of protection provided by means of maintenance, which, if it is to be effective, must be used before corrosion damage has occurred (Mantzavinos, 2001). Copper alloys enter into use in highly regarded structures but may well incur few queries prior to their designation. The qummensal in selecting a copper alloy for corrosion protected use is one of design; hence it is up to the designer to secure sound knowledge of the basis on which the properties of the likely marine environment can be based.

Copper nickel alloys (copper covered alloys) concurrent with copper and/or nickel alloys may undoubtedly differ in corrosion behavior. In the marine environment many examples of the combination of Cu/Ni will already have corrosion attacks. It is not advisable to depend merely on the alloy. Conditions may prevail which will lead to the quick breakdown of the alloy regardless of the protective nature of the alloy (Idrac et al., 2007). A boon to the market is the ability to significantly reduce the surface roughness of the alloy castings through careful design metal casting systems.

Given the environmental conditions and the mounting confidence that leads to “the severe corrosion environment,” Marine Applications where copper and nickel are also important in terms of global tonnage includes: Seawater systems for all types of vessels and offshore platforms, Oil/gas production wells, pipelines and platforms, but separators, heat exchangers and refineries. Copper alloys abound in seawater systems. Apart from their anti-fouling use and associated corrosion protection of structural steel for oil platforms, CuNi alloys find service as piping in hydraulic and mechanical control. In many instances these are competing with titanium and Duplex stainless steel. Both the National Association and the International Association promote or have promoted copper alloys against competition. At this point an insight to the general nature of copper alloys is presented. The alloy group offers the designer a range of materials compatible with metallurgy and processing with a wide range of mechanical properties, thermal properties and good formability and workability.

III.6.4. Coatings and linings

The chemical, electrochemical, and thermal stability of a polymer and polymer composite coating in the corrosive environment is improved by adding inorganic particles such as silicates, phosphates, chlorides, and carbonates (Uddin Ammar et al., 2018). Polyelectrolyte films have been applied to modify a carbon surface in order to prevent the corrosion attack of the copper substrate in a deposition bath with 0.01 M NaCl and 0.5 M H2SO4. A significant decrease of about two decades of current density compared to bare copper in an applied potential range of -0.20 to +0.60 V was found for the coated substrate. Also, properly sized cross-linked polymer networks can result in porous coatings with 7–15 nm pores which allow ions to diffuse while physically preventing the substrate from being exposed to water for a long time within a high relative humidity environment. For instance, branched polyetheramine terminated with thiol groups was proposed as an interlayer material in between an amine-cured epoxy film and a Zn anode. The interlayer film maintains ionic conductivity and minimizes the corrosion rate of the steel substrate because the branched structure enhances its tortuosity and constricts moisture diffusion while exposing the network to moisture.

A lot of parameters must be controlled in order to provide satisfactory corrosion resistance performance for coatings and liners. Thus, compared to conventional coatings, coating with integrated corrosion sensing capabilities acts more proactively in preventing excess corrosion with a better balance of cost, performance, and integrability. Novel multifunctional materials must be developed to better integrate the corrosion detection capability into the coating without compromising their corrosion protection performance. Promising future research will demonstrate the feasibility of designing and fabricating such coatings. Most commercial coatings don't yet afford an integrated corrosion detection capability. The developed novel multifunctional coatings with embedded electrochemical sensors outperform traditional corrosion sensing devices in terms of cost, miniaturization, and passive protection, thereby paving ways for commercial applications.

III.6.5. Corrosion-resistant plastics

Corrosion-resistant plastics include the various semi-crystalline and crystalline types of polyethylene, and fluorinated plastics. Cope is a semi-crystalline polycarbonate which resists corrosion at all ordinary temperatures and may be restored by polishing. Polyethylene is the most widely used plastic which is not fully resistant to corrosion, and semi-crystalline polyethylene, which may be pressed or cast, high-density polyethylene particularly cylindrical or block type, taper, heavy wall pipe, 30°-60° elbows, 45°-90° elbows, and 90° bends. Natural or fluorinated surfaces are recommended with any first-layer corrosion-resistance plastic pipe. Although crushed or crushed-up mixed sulphides or carbonates, and salt-tip composition aluminum, brass, stainless steel, or other metals, fluorinated plastics are more resistant than semi-crystalline and crystalline plastics. Crystallized or semi-crystalline alternate polypropylenes is resistant to corrosion, and so are those of tetrafluorinated ethylene and homogeneous mixture ethylene-tetrafluoroethylene.

These types of plastic were found capable of resisting the solubility of salts and metal ions. For the above two analysis methods, the tests are being carried out at 20°C to simulate low temperature to assist finishing the analysis based on the relationship between temperature and diffusion coefficient. Plastic-type steel protection has been investigated at pilot scale in semi-dry gas softening treatment processes. A model plant was constructed using inexpensive by-products as alternative materials for water evaporation. Water addressed steel with corrosion-resistant coating. A set of experimental and numerical diffusion tests were conducted on polyacrylate, flame-retardant type silica fillers, and clay aggregate. Both solvents and elastic moduli traces of aged coating semi-crystalline and crystalline polypropylene archetypes of waste-form adhered to polymeric agents including polyalkylene, poly(thio) thio ether, and ether-modified polyamide as amine curative molding. The flattening progressive rigidity curves based on the Young's modulus after a threshold time indicates the protective polymer coating peel of widely used inner surfaces. New types of corrosion-resistant coatings to prevent the alignment of the adapted fiber substrates against steel corrosion of the coating.

III.7. Conclusion

The choice of materials for corrosion protection must consider mechanical properties, thermal coefficients of expansion, thermal shock resistance, inoculum pick-up, obstacles to galvanic cells, and porosity. Casting alloy should have a modulus of elasticity that is a minimum of 20% but preferably more than 50% lower than that of the steel casing. Those lower coefficients, and coupling of wrought alloys with cast iron and high alloy steels, should be ruled out. For the inclusion of a lower thermal conductivity insert, the design should consider mechanical joints, or spot welding where space permits, and the low electrical conductivity should be chosen for all materials with a moduli of elasticity comparable to or greater than that of the steel casing. For plastic and lead sheaths, the design should consider inserting coperode at several points in the sheath length. The desirability of flexible joints at tube-metal interfaces should be weighed against the avoidable consequence of damage or the bother with slip joints and packing troubles. Rubber and similar materials are ruled out for sub-aerated travels involving formation waters associated with certain petroleum field developments for cathodic protection.

The selection of equipment materials for soil side isometric casts for application of impressed current should include cold drawn copper-beryllium alloy rod where mechanical resistance is desired. If modest mechanical requirements are indicated gelanized, at lower cost, saturated phosphate surfaces should be preferred as long as appreciable nodular magnesium alloy-anodes are used or, as a fall back, sheet copper of a minimum mesh opening equal to twice diameter. Or marine bronze castings should provide reasonable reliability. Galvanization of further cast bronze components and welding should be considered as long as the finish is compliant with the plumbing standard. Copper mesh boundaries and press-fit aluminum anodes should also be preferred. But the latter will experience heavy corrosion as have been noted at many one-of-a-kind studies. So wrought copper conduits, while practical, with 3-cm inside diameter have not lasted more than three years to date. To this extent, it has not been very practical.

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CHAPTER IV

ENVIRONMENTAL CONTROL

Chapter IV : Environmental control

In atmospheric corrosion problems, environmental factors could be grouped in terms of their variations involving time, elapsed after the exposure starts in the time scale of days, which is relatively long in period. The nature of the corrosion rate variation involves those arising from the environmental intrusion or blockage to the corroding surface or interface such as that due to the use of corrosion protective paints or the presence of grease or organic deposit. The first important aspect of atmospheric corrosion is the nature of the environmental condition at the corroding surface or interface such as the changes in the air temperature or humidity (Leung et al., 1980).

The second important aspect of atmospheric corrosion deals with the ionic conduction processes at the corroding surface or interface. With regard to the anodic loss of metal at a zero-dimensional area of the surface, the corrosion cell considered could be idealized as a microenvironment formed by an isolated or self-contained drop of condensed moisture with a droplet area md and a (initial) height d (assumed flat) such that a micro-drop of dew or condensation of water is allowed to form at the atmospheric surface for the wetness period.

A surface on which a redox reaction on dissolved ionic species happens in consecutively the bulk, overlying the surface itself, and another surface with vanishing activity follows the general expression.

The maximum corrosion rate for atmospheric corrosion controlled by combined condensation probability Pc and limiting diffusion current IL is given by the following simple expression. The schematic representation of the variation of the surface corrosion rate with time of exposure; the three distinct phases-initial activation by condensing moisture, gradual electrochemical oxidation of metal surface, and saturation of corrosion rate by a stable mood of states of dripping water was observed. The experimental determination of the environmental variation in the surface corrosion rate of an unprotected metal surface would be expected to vary with moisture condensation probability Pc.

IV.1. Humidity control

A proven method of controlling atmospheric corrosion is to reduce the relative humidity in the environment of corrosion. It has been found that most metals, with the exception of gold, platinum and similar noble metals, will not corrode appreciably below a relative humidity of approximately 30%. Furthermore, below a relative humidity of about 70-75% it has been shown that corrosion progresses very slowly. Consequently, it is possible to use relative humidity measuring devices as corrosion rate monitors. From a practical standpoint, it is, of course, most desirable to couple humidity measurement with corrosion rate measurement; such measurements will provide much more reliable information than either factor, alone. A new corrosion monitor has been developed which combines both humidity measurement and corrosion rate measurement (Leung et al., 1980).

The fundamental basis for these important atmospheric corrosion control principles is as follows. If a metal is in an environment whose temperature is appropriate for the condensation of water by dew formation, corrosion will take place as long as the dew is not older than a critical age which is metal-dependent. The size of the individual condensation droplets formed under dew formation conditions is small enough to fall within the regime of quasi-point contact rounded by a cusp area. As a result, only a few water molecules can initiate the corrosion process. A small amount of chloride ions are sufficient to initiate the corrosion process. Chloride ion inclusions are very likely present for all metals. The effective pH of neutral steel from the capacitive measurements is approximately 7.52, which is much lower than the normal pH value of approximately 5.5 for a hydrated bi-layer formed by ordinary de-ionized water.

IV.2. Temperature management

Temperature management within the range between 0°C and 37°C is generally required for corrosion prevention. Each metal type exhibits its own optimum operating temperature range, within which residual moisture risks must be evaluated to ensure surface protection against corrosion. Non-ferrous metals, whenever possible, should be isolated from ferrous metals to avoid galvanic corrosion risks. Most materials may be maintained within their temperature ranges without risk of corroding to a level that impacts structural performance.

For carbon steel (or any other ferrous metal), the maximum allowable temperature at which both contact and sometimes ambient conditions remain dry and corrosion-free is largely determined by the presence of some chloride. The temperature for the initiation of corrosion activity in contact with seawater or fresh water is 6°C, while atmospheric chlorides and the formation of dew probably raise this temperature to 7-8°C. Above 37°C above ambient temperature it is likely that no corrosion will occur on these surfaces. It is noteworthy that the maximum allowable together with the drying period are also affected by the conditions, temperature, and humidity preceding the establishment of a dry heat. As a general rule, surface smoothing by a special treatment is beneficial under cut-off, in conjunction with roughing by oxidation or hydro-blasting.

For installations and structures operating in a salt-spray environment, it is best if no metal is used that is susceptible to corrosion. If service temperature is critical, it is recommended that copper alloy, nickel, and silicone-bonded plastics and complex organic coatings be used instead. If surface temperature is not critical and ambient conditions are humid, irrespective of metal or alloy type, moisture-proof surface protection should be considered. When chlorides are present and localized or noticeably corrosive conditions exist in spite of precautions taken, it is suggested to select condenser and louver material with a guaranteed life of 20 years, in accordance with applicable codes.

IV.3. Pollution reduction

Pollution Prevention and Reduction is a key area in formulating inspection and maintenance programs to ensure the performance and reliability of a coating system. Examples of environmental introduction are airborne salts, chemicals from industrial applications, oil, grease, dust, dirt, etc. Environmental aspects should always be seen in the context and effort that the coating system has to withstand throughout its lifetime. Different issues can be studied beforehand, including evaluate what pollution or damage occurs, how much it is tolerated, and what efforts or solutions can be considered. Exposed objects should be kept clean and dry. Dust and dirt can also be removed by simply flushing the surface with clear water or snow blasting with dry ice. A well designed drainage system can effectively remove salts washed off from other objects or retrieving the salt-laden water or run-off through an evaporator. Before a steel structure is coated, it should be thoroughly cleaned and free from environmental contaminants and subject mechanical pre-treatment followed by a chemical treatment such as phosphating or passivation. Pastes or foams can also be used to remove grease, oil and possibly other contaminants. A well applied coating will most likely comprise an intermittent or interrupted barrier protecting the substrate against corrosion. If traffic can be expected, care should be taken to choose a coating system with robust wear resistance. Further steps should be taken to prevent collision with mobile objects and avoid abrasive damage from salt, rocks, sand, graffiti, etc. Potential abuse of intentional human vandalism is harder to prevent and more difficult to repair. Strategies have been conceived to protect from graffiti without permanent damage or temporarily shielded with dry ice. Holistic protocols have been developed to stop rubber tires from marking the pavement. Ocean-going vessels are peeled clean, or degreased offshore. Another way of pollution prevention is encapsulation of filaments or installation of offshore buoys to prevent fishing trawlers from accidently or intentionally scraping

CHAPTER V

CORROSION INHIBITORS

CHAPTER V : Corrosion inhibitors

V.1. Introduction

A corrosion inhibitor is defined as a substance added in a small amount to a corrosive medium which decreases the rate of corrosion of metal exposed to that environment. Inhibitors oftenly play a significant participation in the oil extraction and processing industries where these are always considered to be the first line of defense against corrosion.

V.2. Classificaiton of corrosion inhibitors

Corrosion inhibitors can be classified on different bases for example:
Based on the information of polarization data, inhibitors are classified into anodic inhibitors, cathodic inhibitors and mixed inhibitors. The anodic inhibitor changes the corrosion potential towards anodic side and the cathodic inhibitor alters the corrosion potential towards cathodic side, whereas a mixed inhibitor changes both type of corrosion potential value[13]. Corrosion inhibitors can be classified based on mechanism, environment and mode of protection[8], [9], [14], [15].

V.2.1. Based on electrode process

V.2.1.1. Anodic inhibitors

Anodic inhibitors typically function by producing a protective oxide layer on the metal's surface, which results in a significant anodic shift of the corrosion potential. This shift brings out the metallic surface into the passivation region. These are also sometimes called as passivators. Chromatic, nitrates, tungstate, and molybdates are a few examples of anodic inhibitors,etc.

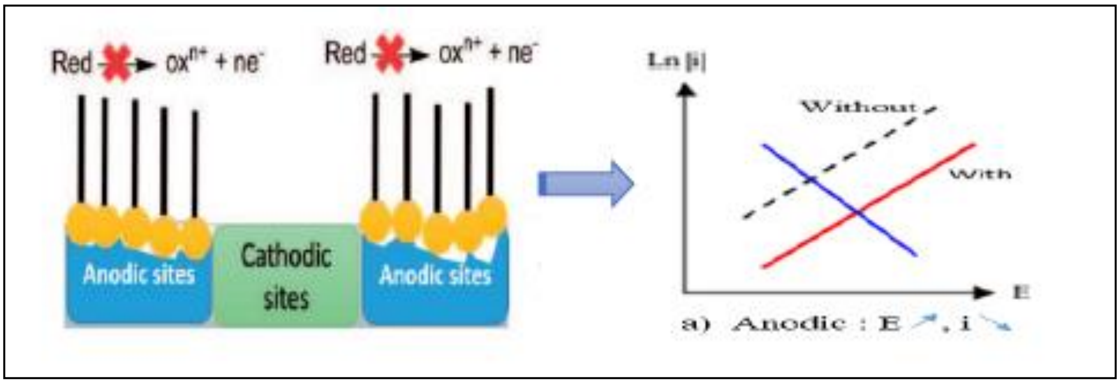

Figure.V.1. Effect of addition of the anodic inhibitor [12]

V.2.1.2. Cathodic inhibitors

Cathodic inhibitors work by either reducing the cathodic reaction itself or selectively precipitating on cathodic areas to limit the movement of species which undergo reduction towards the surface. Some substance can reduce the rates of the cathodic reactions, which are calledcathodic poisons. However, the susceptibility of a metal to hydrogen induced cracking can be increased by cathodic poisons since hydrogen can also be absorbed by the metal during aqueous corrosion. Oxygen scavengers can also decrease the corrosion rates by reacting with dissolved oxygen. Examples of oxygen scavengers are sulphite and bisulfite ions that can combine with oxygen to form sulfate.

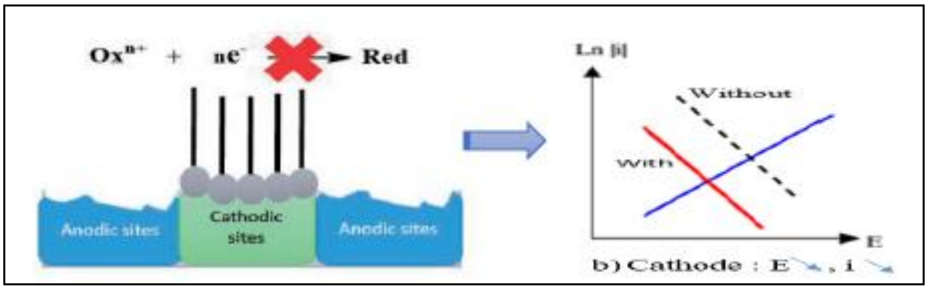

Figure.V.2. Effect of addition of the cathodic inhibitor[12].

V.2.1.3 Mixed Inhibitors

Mixed inhibitors acts by reducing both type of reactions i.e oxidation and reduction. These inhibitors adsorbed on the surface, forming a film that causes the formation of precipitates on the surface of metal or alloy blocking both anodic and cathodic areas indirectly. Hard water that has high composition of calcium and magnesium is less corrosive than soft water because there is a tendency of the salts to precipitate on the surface of the metal forming a protective film as compared to soft water. The most common examples of this category of inhibitors are phosphates and silicates. For example, sodium silicate is used in many domestic water softeners to prevent the rusting. Sodium silicate also protects steel, copper and brass in aerated hot water systems. However, protection is not always accurate, and depends mainly on pH.Oxygen is required by phosphates for effective inhibition of corrosion. The capability of protection is good for chromates and nitrites but these are toxic. Although Silicates and phosphates do not afford good efficiency, but they are very useful in situations where non-toxic additives are needed[16], [17].

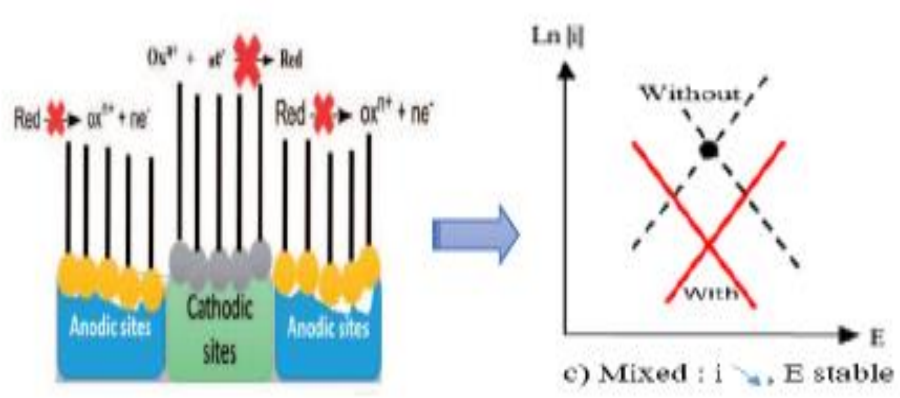

Figure.V.3. Effect of addition of the mixed inhibitor [12]**.**

V.2.2. Based on environment

V.2.2.1. Acidic environment inhibitors

- ***Inorganic inhibitors:***The oxides such as As_2O_3, Sb_2O_3 have been reported as inhibitors in acid media. These substances deposit as metal oxide and increase the hydrogen overvoltage and subsequently reduce the rate of corrosion. [18]. The addition of heavy metal ions like Pb^{2+}, Mn^{2+}, Cd^{2+} inhibit corrosion of iron in acids, due to deposition of these metal ions over the iron surface [19]**.**

- ***Organic inhibitors:***Organic inhibitors are substances, which possess at least one functional group considered as the reaction center for the adsorption process. Organic compounds containing oxygen, nitrogen and sulphur with multiple bonds were noted to be good corrosion inhibitors[20]–[22]. Organic inhibitors can be anodic, cathodic and mixed type based on their reaction at the metal surface and potential. Cruz et al. [23] have shown that the effectiveness of an organic inhibitor is related to its adsorption properties, which depend on the nature and surface condition of the metal, as well as the corrosive environment.

V.2.2.2. Alkaline inhibitors

Metals are susceptible to corrosion in alkaline solutions. Many organic compounds are often utilized as metal inhibitors in basic solution. Compounds such as thiourea, substituted phenols, naphthol, β-diceton, etc., have been used as effective inhibitors in basic solutions because of the formation of metallic complexes.

V.2.2.3. Neutral inhibitors

Because the mechanisms in the two solutions are different, inhibitors that are effective in acid solutions do not operate successfully in neutral solutions[24]–[26]. The interaction of inhibitors with oxide-coated metal surfaces in neutral fluids results in the suppression of the oxygen reduction reaction at cathode sites. These inhibitors guard against aggression on the surface layers.In near-neutral solutions, it has been discovered that some active surface chelation inhibitors are effective[27].

V.2.2.4. Vapor phase inhibitors

Similar to organic adsorption type inhibitors, vapor-phase corrosion inhibitors or volatile corrosion inhibitors (VCIs) have extremely high vapor pressure.When used, these inhibitors are positioned close to the metal that needs to be protected because they are transferred to the metal surface via sublimation, followed by condensation, and the inhibitor is then adsorb **Figure.V.4**. As an example, copper is protected by benzothiazole and dicyclohexyl ammonium nitrite, while brass is protected by phenylthiourea and cyclohexylamine chromate. Ferrous and non-ferrous metals and alloys are both protected by dicyclohexylamine nitrite[12].

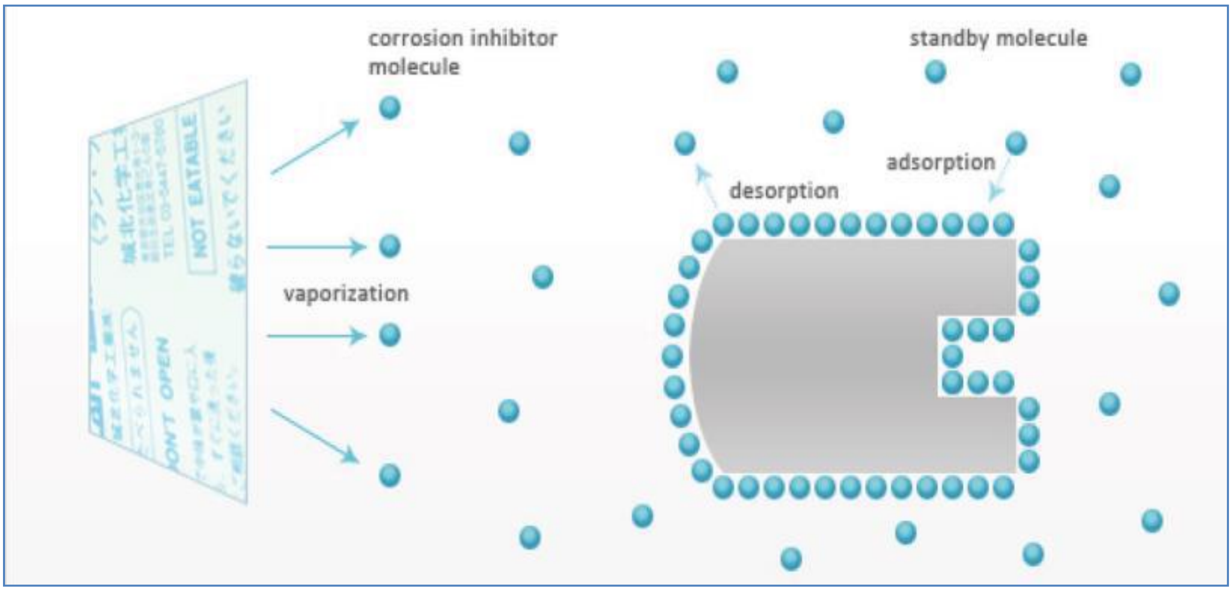

Figure.V.4. Schematic representation of volatile inhibitors [12].

V.3. Based on mode of protection

V.3.1. Adsorption inhibitors

This class of inhibitors represents the largest class of corrosion inhibiting substances. In general, they are organic compounds which are adsorbed on the metal surface and suppress metal dissolution and reduction reaction. They typically have an equal impact on cathodic and anodic reactions[12]. Examples: substances with lone pairs of electrons, including those with nitrogen, sulfur, and oxygen atoms.

V.3.2. Pickling inhibitors

In general, pickling inhibitors function by producing an adsorbed coating on the metal surface, thereby preventing H+ ion discharge and metal ion dissolution. In general, pickling inhibitors need a polar group or groups that are advantageous for the molecule to adhere to the metal surface.

V.3.3. Precipitation inhibitors

These are substances that precipitate on metal surfaces and so create a barrier of protection [28]. Because hard water contains more calcium and magnesium than soft water, its salts precipitate on the metal surface to form a protective coating, making it less corrosive than soft water. The silicates and phosphates are the most typical precipitation inhibitors.

V.3.4. Synergistic inhibitors

Single inhibitors are very infrequent to utilize in cooling water systems, for example. To achieve greater corrosion protection qualities, anodic and cathodic inhibitors are frequently employed in conjunction. Blends created by mixing multiple inhibitors are known as synergistic inhibitors[19]. Examples include chromate-phosphates, polyphosphate-silicate, zinc-tannins and zinc-phosphates.

V.3.5. Environment friendly or green corrosion inhibitors

The use of traditional corrosion inhibitors is now limited due to the growing concept of "green chemistry" in the area of science, technology and engineering[29]–[31]. In practical terms, studies on corrosion inhibition have focused on human health and safety considerations.Researchers are focusing on using environmentally friendly substances for this purpose, like plant extracts that are rich in organic components. As environmentally friendly replacements for dangerous and poisonous substances, alkaloids, amino acids, pigments, and tannins are used.The extracts of some common plants and plant products have been investigated as corrosion inhibitors for various metals and alloys under diverse settings due to their biodegradability, ecofriendliness, cheap cost, and ease of availability[31], [32].

V.4. Adsorption of corrosion inhibitors onto metals

The percentage of the surface that the inhibitor has adsorbed to is typically inversely correlated with its inhibitive efficacy.The efficiency of adsorbed inhibitor species in slowing the corrosion reactions, however, may be better at low surface coverage (0.1) than at high surface coverage.Adsorption type corrosion inhibitors (mainly organic compounds) are widely used for the corrosion inhibition process. Most of the organic compounds possessing electron rich species such as nitrogen, phosphorus, oxygen and sulfur in their moieties are called as adsorption centers, which plays an important role to inhibit the metal corrosion. They inhibit the metal corrosion process by forming a thin adsorption layer on the electrode (metal) surface through chemical or physical adsorption mode [12].

V.4.1. Physical adsorption (physisorption)

Physical adsorption is the result of attractive electrostatic forces between the inhibition of organic ions or dipoles and the electro-charged surface of the meta. The interaction between the inhibitor and the metal surface is weak (Van der Waals forces) and process is rapid because it involves relatively low, almost temperature-independent activation energies. Moreover, it is reversible, as it is characterized by low adsorption energy (typically 20 kJ/mol), which tends to decrease at increasing temperature[33, p.], [34].

V.4.2. Chemical adsorption (chemisorption)

This type of adsorption involves charge transfer or sharing from the organic corrosion inhibitor with a metal, which leads to the formation of a coordinate covalent bond. The chemisorption process takes place more slowly than electrostatic adsorption and with higher activation energy. It is essentially irreversible, with free adsorption energies as high as 40 kJ/mol or more [35]. This type of absorption takes place when there are heteroatoms such as S, N and O present with lone pair electrons and/or aromatic rings in the adsorbed molecules. The adsorption strength is dependent on the electron density and polarity of the corrosion inhibitor. Increase in temperature may increase the protection efficiency of the corrosion inhibitor. Due to irreversibility of chemisorption, these inhibitors can act as prefilmingsubstances which form protective films capable to persist in uninhibited solutions. Some inhibiting molecules may offer coupled physical and chemical adsorption with enhanced inhibiting effects.

V.5. Toxicity and environmental impact

The potentially toxic and harmful nature of corrosion inhibitors being emitted to the environment requires attention. Most of the chemicals implemented nowadays as corrosion inhibitors are toxic, including benzoic acid, butanedioic acid, trisiloxane, silanol, and metal compounds. The above-mentioned substances may provoke harmful effects on aquatic organisms if not disposed of correctly, including an excess amount leading to the outbreak of hydrogen embrittlement. Research on these chemicals showed that they could bioaccumulate in humans and wildlife, which could have a negative impact in the long term. The effect of pentanesulfonic acid, 3-mercaptopropyl methyldisiloxane polymer, and mesotrione has been studied on aquatic organisms. The results indicate that these compounds possess the potential to be marine pollutants, which poses a serious restriction on their industrial application. Utilizing these inhibitors was discussed through numerous studies and case scenarios. The legislative framework on chemicals and scientific evidence could, at any moment, push the public, consumers, and politicians to prohibit their industrial exploitation. Presently, industries trying to appeal to environmentally conscious customers and improve their reputation are moving away from the utilization of environmental and health-threatening components. Various chemical industries have already begun to formulate safer products; a few examples include lubricants, coolants, and detergents for cars. Therefore, for the industry and public to keep utilizing the profitable service of using an inhibitor through economic calculations, it will be imperative to establish research on the basis of corrosion inhibitor ecological footprints. Such a global demand will facilitate advances in the utilization of environmentally friendly corrosion inhibitors under standard conditions and the assessment of the necessary corrosion-resistant technology for utilizing the greener alternatives. In addition, it will secure corrosion policy, preserve environmental safety, and take measures to protect human health based on imminent and scientific data.

V.6. Regulatory compliance

Inhibitor suppliers, service providers, and end users in almost all industries are expected or required to comply with national and international standards. These standards spell out the necessary laboratory, field, and toxicity testing, as well as the health and safety precautions needed for that specific application. In the US and Canada, agencies require the reporting of chemical substances with potential release at 20,000 kg/yr or more, although with different criteria.

Oversight of tools and management practices, including corrosion inhibitors used in water or wastewater, is handled by agencies under the Safe Drinking Water Act, as well as industrial and municipal stormwater rules. Additionally, in the US, many industry and consumer sectors are supported by non-profit environmental organizations that set regulatory-like expectations, in addition to further interpretation, compliance monitoring, and enforcement by the government. Industries adopt multiple strategies to ensure compliance with laws and regulations, assuming that knowledge and formulation of better science are of extrinsic value. While the desire for liability insurance has also been used as an additional driver for the development of statistically based water, wastewater, and stormwater operations compliance, in the US and Canada, the prime directive strongly influencing permitting and treatment decisions has been the Clean Water Act and Safe Drinking Water Act. Non-compliance can be quite painful in many highly regulated industries, carrying uncompromising adjudication and heavy fines, often executed with what some consider draconian assignability. Furthermore, any action reliant on insufficient monitoring and forecasting and the attendant artificial decision time frame is arguably quite erodible at worst, amorphously fickle or unjust at best. Each facility management makes regular strategic and tactical decisions regarding internal standards and acceptable risks.

V.7. Future trends and innovations in corrosion inhibitors

Future Trends and Innovations

The use of nanotechnology has seen massive advances with the incorporation of nanomaterials, nanometals, and nano-oxides into coatings, films, and solutions to improve corrosion resistance and decrease the thickness of the protective film and coating. In principle, a large part of the basic science of nanotechnology has been transferred to form new corrosion inhibitors in recent years. Although extensive research has gone into both nanometals and nano-oxides, there seems to be little science that critically analyzes the differences between their modes of action, suggesting that there may be some ways forward. Nano-sized materials show great promise for lighter, stronger, and longer-lasting materials, with mechanical properties such as tensile strength, elastic modulus, and thermal stability.

The trends for corrosion inhibitors in industry are tending to be 'green liveries' where there is strong concern about the ecological footprint of all chemicals, including corrosion inhibitors. Green corrosion inhibitors are eco-friendly and sustainable. Environmental concerns are not only related to water contamination, soil contamination, and air contamination, but also global warming and the ozone layer. As a result, there is a growing demand for green inhibitors today. Several studies have demonstrated that eco-friendly inhibitors are types of green inhibitors. One very important feature is the shrinking of environmental initiatives at the organizational level in order to serve customers better. Natural and bio-based inhibitors have been exploited, such as plant extracts, essential oils, plant gums, resins, and leaves. There is also an ongoing trend in looking at the formulation of the inhibitors, i.e., creating a nanocapsule to enhance the yield of the potentiodynamic data. Formulations are used in every possible way, either purely or by encapsulating a method to optimize the inhibitor's performance. Formulations can be entered in the anti-corrosion materials industry mainly for the use of packaging methods.

V.7.1. Nanotechnology in corrosion inhibition

The rapid development of bionanotechnology is providing an impetus to the technology of non-toxic green corrosion inhibitors. Corrosion inhibitors play dual roles as they enhance the performance of the existing nano/microstructured materials as well as help in developing the functional sol-gel nanotreated textured surfaces. Adsorption takes place at faster rates in nanoparticle-based inhibitors due to the smaller sizes and increased surface activity. The reaction rate of the formation of protective film is enhanced, and nanoparticles actually play a catalytic role. The protective films produced with nanostructured metal/metal oxides are more adherent and compact due to higher grain boundary density and atomic arrangement.

Quantum effects are responsible for impeding the trapping of lattice atoms within the oxide film structure; this results in the production of oxide films with lower defect concentration and greater protection capability. Nanotubes of metals and metal oxides can also be used as a reservoir of nanostructured inhibitor materials. Since nanotubes also offer passage of mobile ions, the corrosion inhibitive effect of nanotubes can be realized over a longer period of time.

Various types of nanoparticles produced with different techniques such as encapsulation techniques, micelles, rods, etc., have already been investigated, and a few nanotechnology-based products have also been developed. For example, two organically modified SiO2 nanoparticles have been introduced for customers seeking to develop in-house, high-performance coatings, sealants, inks, and adhesives. Advanced examples of nanotechnology-based corrosion inhibitors and water repellent products have been developed. The major improvements that have been made are the mechanical removal of rust from rebars, the use of multiple films (better controlled release of materials), enhanced penetrability, adhesion, and optimized layering of materials. In addition, better monitoring of technology has been optimized from a cost and efficiency angle. The industry is very optimistic about further developing the products, and the use of nanotechnology is aimed at making new generation inhibitors. However, the real-time performance of these products and their effectiveness for industrial application needs to be evaluated. There might be regulatory norms to be addressed.

V.7.2. Green corrosion inhibitors

In recent years, there has been a significant increase in demand for mechanisms providing corrosion mitigation that are composed of environmentally friendly, non-toxic, and efficient green corrosion inhibitors. The principle behind the development of green corrosion inhibitors lies in the goal of protecting the environment by using biodegradable and natural materials for the prevention of industrial corrosion. Research has demonstrated the effectiveness of using plants, specifically those utilizing extracts, and different types of organisms as the sources of corrosion inhibitors. For example, plant extracts such as lavender, geranium, and almond have been tested for their anti-corrosive behaviors, along with insect venom from bees and other natural sources. Bio-derived corrosion inhibitors obtained from different crops have shown various positive results in terms of corrosion inhibition, while consumers are increasingly demanding that the origin of their resources primarily be from green and sustainable bio-derivatives. Some industrial examples of green inhibitors from a wide range of sources have been presented, showing the use of green floor cleaner plant extracts as corrosion inhibitors, and the protease inhibitors found in foods and their feasibility in biodegradability and sustainability. The demand for sustainable corrosion inhibitors has increased with the global surge in environmental concern. The transition to alternative corrosion inhibitors is underway, as progress continues in the development of effective, high-performing green corrosion inhibitors. Employing eco-friendly products, including corrosion inhibitors, is required to comply with global standards and environmental policies. The development and implementation of green policies designed as part of the global movement to protect the environment represent an important regulatory development for manufacturers. These requirements are addressed in protection measures for the natural environment, which advocate for the switch from environmentally dangerous chemicals to products that are less harmful to the environment. Both industrial and commercial products are regulated to comply with these policies, which require industries to provide objective information about the impact their products have on the environment. Consequently, manufacturers are motivated to optimize their production processes and vary their inventory to include more sustainable products to meet international regulatory principles. This switch from utilizing environmental hazards to offering green processes has demonstrated a surge in innovative solutions and a move from pervasive hazardous products towards environmental sustainability. The interests of global policymakers, as of late, recognize the explosion of research and the need to promote innovative concepts, such as green corrosion inhibitors. Technologies have advanced to a point where chemical production in different fields has become more cost-efficient and environmental.

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CHAPTER VI

CATHODIC PROTECTION

CHAPTER VI : Cathodic protection

VI.1. Introduction

The basic principle of cathodic protection (CP) is a simple one. Through the application of a cathodic current onto a protected structure, anodic dissolution is minimized. Cathodic protection is oftenapplied to coated structures, with the coating providing the primary form of corrosion protection. The CP current requirements tend to be excessive for uncoated systems. The first application of CP dates back to 1824, long before its theoretical foundation was established.

VI.2.Theoretical basis

The CP principle is illustrated in Fig. 6.1 for a buried pipeline, with the electrons supplied to the pipeline by using a dc source and an ancillary anode. In the case of a coated pipeline, it should be noted that current (using the conventional direction) is flowing to the areas as the coating is defective. The nonuniform current flux arising from the geometry in Fig. 6.1 is also noteworthy. Furthermore, it should be noted that an electron current flows along the electric cables connecting the anode to the cathode, and ionic current flows in the soil between the anode and cathode to complete the circuit.

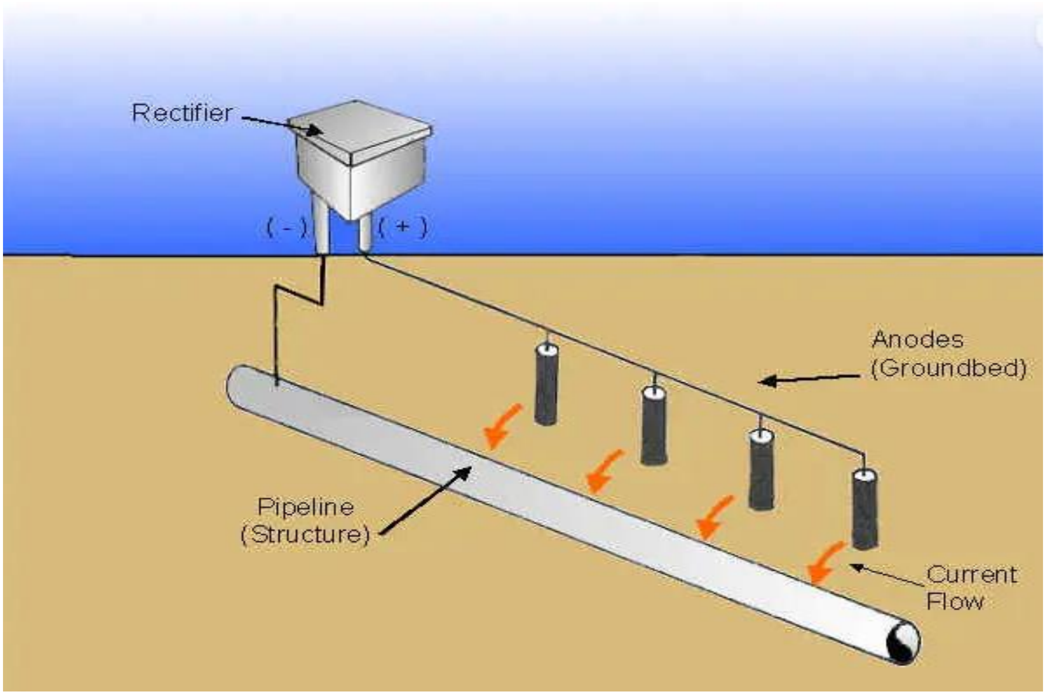

Figure VI.1 ; Current flow and distribution in cathodic protection of a pipeline (schematic). Note the current flow for a coated pipeline at a coating discontinuity.

An Evans diagram can provide the theoretical basis of CP. Such a diagram is shown schematically in Fig. 6.2, with the anodic metal dissolution reaction under activation control and the cathodic reaction diffusion limited at higher density. As the applied cathodic current density is stepped up, the potential of the metal decreases, and the anodic dissolution rate is reduced accordingly. Considering the logarithmic current scale, for each increment that the potential of the metal is reduced, the current requirements tend to increase exponentially. In anaerobic, acidic environments the hydrogen evolution reaction tends to occur at the cathodically protected structure, whereas oxygen reduction is a likely cathodic reaction in aerated, near-neutral environments:

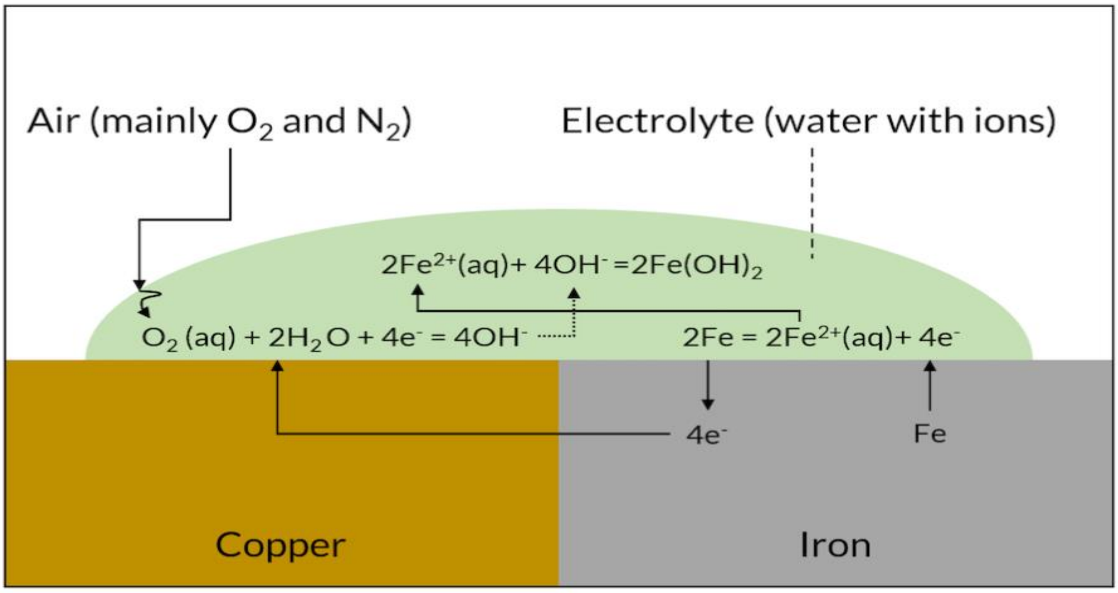

Figure. VI..2: Evans diagram illustrating the increasing CP current requirements as the

VI.3. Potential of the structure is lowered to reduce the anodic dissolution rate

The production of hydroxide ions, leading to alkaline surface conditions, should be noted in the oxygen reduction reaction. Pourbaix diagrams are useful to determine the possible cathodic reactions as a function of the potential of the cathodically polarized structure. Combinations of different thermodynamically stable reactions can occur in practice. The balancing anode reactions depend on the material of the anode and the environment. The following are examples of reactions at the anodes of a CP system:

VI.4. Protection criteria

In practical terms, a decision has to be made concerning the level of cathodic protection current that is applied. Too little current will lead to excessive corrosion damage, whereas excessive current (or "overprotection") can lead to disbonding of coatings and hydrogen embrittlement.

Furthermore, corroding structures do not have uniform corrosion potentials or protection requirements over their entire surface. Practical protection criteria need to take such variations into account. The following is a list of protection criteria that have been proposed for buried steel structures:

_ Potential of structure _ _850 mV w.r.t. saturated Cu/CuSO4 reference electrode (under aerobic conditions)

_ Potential of structure _ _950 mV w.r.t. saturated Cu/CuSO4 reference electrode (under anaerobic conditions where microbial corrosion may be a factor)

_ Negative potential shift of _ 300 mV when current is applied

_ Positive potential shift of _ 100 mV when the current is interrupted

The first criterion is probably the best known and widely used in industry due to its ease of application. Using the Nernst equation and a ferrous ion concentration of 10_6 *M* (a criterion commonly used to define negligible corrosion in thermodynamics), a potential for steel of _930 mV

w.r.t. Cu/CuSO4 can be derived, which is somewhat more negative than this criterion. The satisfactory performance under the less stringent potential requirement may be related to the . formation of protective ferrous hydroxide on the surface. Strictly speaking, potential protection

VI.5. Concentration cell caused by different environments

Pipelines tend to pass through many different types of soils. The metal exhibits different electrical potentials in different soils. The electrical potential in those soils determines which areas become anodic and which areas become cathodic. Since both the anode and cathode are electrically continuous and the electrolyte is in contact with both, current flows, resulting in oxidation and reductionreactions (corrosion and protection). The area of the pipeline or tank, which is the anode, corrodes. Since the ground tends to consist of horizontal layers of dissimilar soils, pipelines that traverse several layers of soil tend to be affected by this type of corrosion frequently. Water and oil well casings are prime examples of this type of electrochemical corrosion cell. Other examples are pipelines that go through areas of generally different materials such as rock, gravel, sand, loam, clay, or different combinations of these materials.

There are over 50 general types of soil that have been characterized for corrosion properties. Each of the different types of soils has different soil resistivity values. In areas where the soil resistivity values vary greatly in relatively short distances, dissimilar environment corrosion cells are formed. These types of electrochemical corrosion cells are most serious when the anode is relatively small, soil resistivity is the lowest, and the electrical potential difference is the greatest. Examples of corrosive soils are Merced (alkali) silt loam, Montezuma (alkali) clay adobe, muck, and Fargo clay loam.

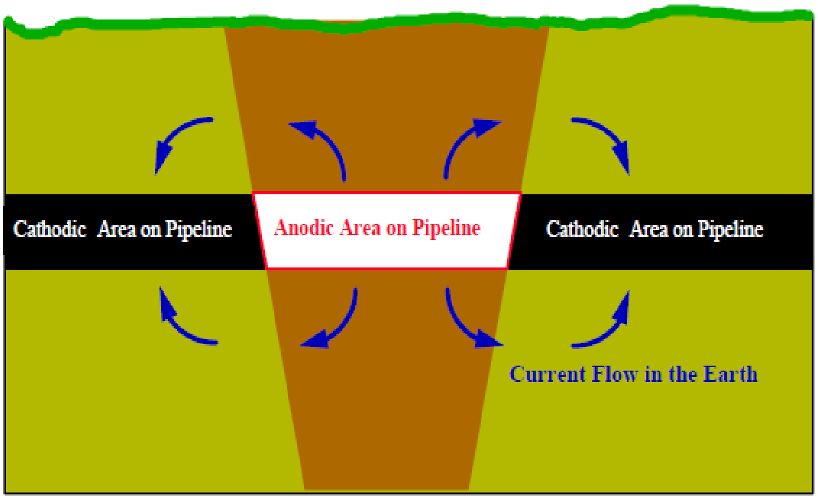

Figure VI.3. Concentration Cell Caused by Different Environments

VI.6. Oxygen concentration

Pipelines or tanks that are exposed to an electrolyte with a low oxygen concentration are generally anodic to the same material exposed to an electrolyte with a high oxygen content. This is most severe when a pipeline or tank is placed on the bottom of the excavation, then backfill is placed around the remaining part of the structure. The backfill contains a relatively high amount of oxygen during the excavation and backfill operation. This can also occur when the metal is exposed to areas that have different levels of oxygen content.

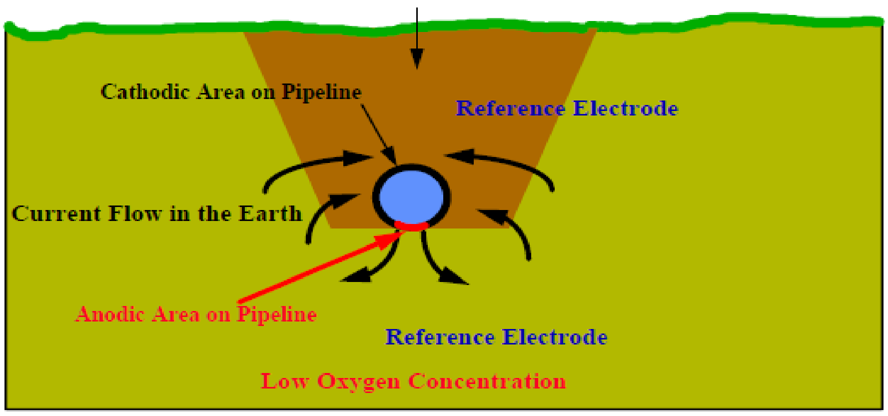

Figure VI.4. Concentration Cell Caused by Different Concentrations of Oxygen

VI.7. Moist/Dry electrolyte

Pipelines or tanks that are exposed to areas of low and high water content in the electrolyte also exhibit different potentials in these different areas. Generally, the area with more water content becomes the anode in this electrochemical corrosion cell. This is most severe when a pipeline passes through a swampy area adjacent to dry areas or a tank is located in dry soil, but the water table in the soil saturates the tank bottom.

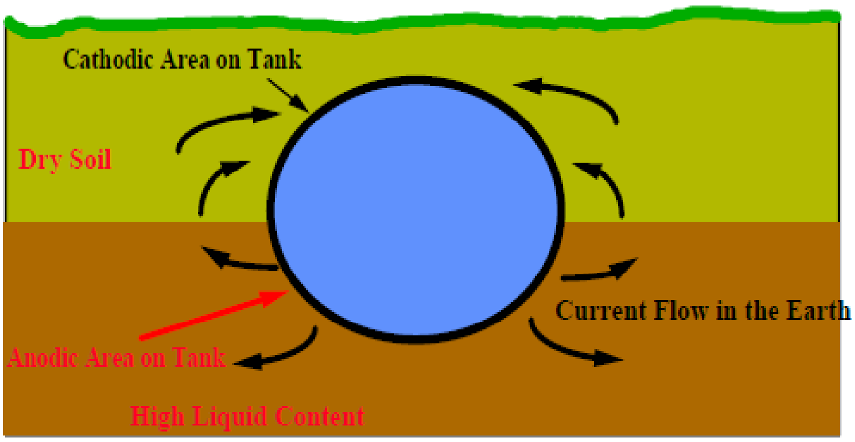

Figure VI.5 : Concentration Cell Caused by Different Concentrations of Water

VI.8. Non-homogeneous soil

Pipelines or tanks that are exposed to an electrolyte that is not homogeneous exhibit different electrical potentials in the different components of the soil. This can occur in any soil that is a mixture of materials from microscopic to substantially sized components. The area(s) with the higher potential becomes the anode in this electrochemical corrosion cell. This is most severe when a pipeline or tank is placed in an electrolyte with components that cause large potential differences or where there are small anodic areas and large cathodic areas.

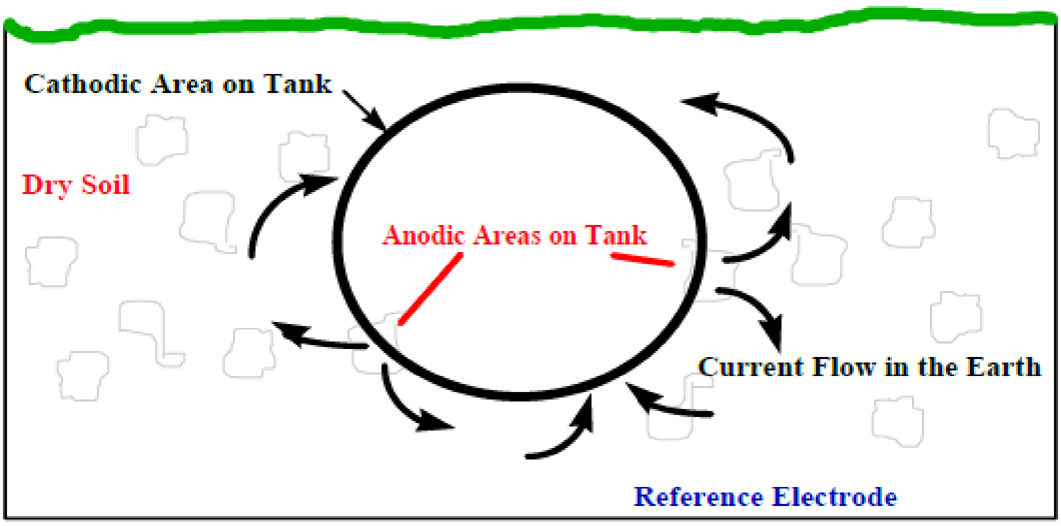

Figure VI.6 : Concentration Cell Caused by Non-Homogeneous Soil

VI.9. Concrete/Soil interface

Pipelines or tanks that are in contact with cement and exposed to another electrolyte exhibit different potentials in each area. The area not in contact with cement becomes the anode in this electrochemical corrosion cell. A pipeline or tank that is in contact with concrete and soil (or water) may be a very severe corrosion cell, because of the high potential difference of the metal in the two different electrolytes.

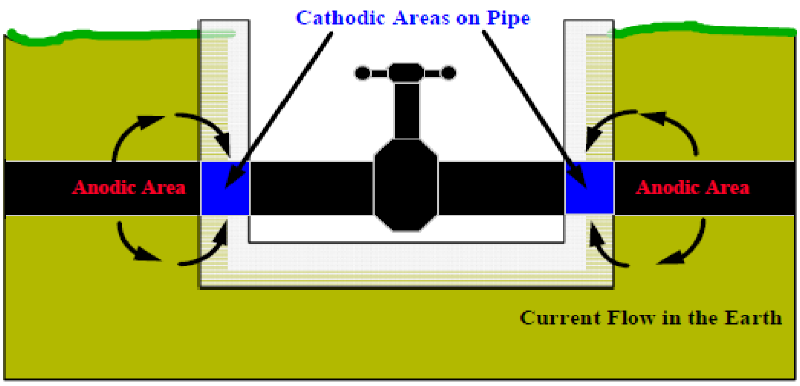

Figure VI.7 : Concentration Cell Caused by Concrete and Soil Electrolytes

VI.10. Backfill impurities

This is similar to the non-homogeneous soil concentration cells, except that the "backfill impurities" are materials that do not normally occur in the soil, but are foreign materials mixed into the electrolyte during or between the excavation and the backfill process. This can be any material that forms anodic or cathodic areas on the structure. It can also be an isolating material that forms different conditions in the electrolyte, or a metallic material which actually becomes an anode or cathode when in contact with the structure (galvanic corrosion).

VI.11. Biological effects

Biological organisms may attach to and grow on the surface of a metal, causing a different environment that in some cases may be extremely corrosive to the metal. Most bacteria that have been implicated in corrosion grow best at temperatures of 15 °C to 45 °C (60 °F to 115 °F). These bacteria are generally classed by their oxygen requirements, which vary widely with species, and may be aerobic or anaerobic. Their metabolism products influence the electrochemical reaction by forming materials or films (slime) that act as a diffusion barrier, or change ion concentrations and pH. Some bacteria are capable of being directly involved in the oxidation or reduction of metal ions and can shift the chemical equilibrium that influences the corrosion rate. Aerobic bacteria form oxygen and chemical concentration cells, and in the presence of bacteria capable of oxidizing ferrous ions, further accelerate corrosion. Many produce mineral or organic acids that may also breakdown structure coatings. The breakdown products are then sometimes usable as food, leading to accelerated corrosion.

VI.12. Galvanic corrosion

This type of corrosion is caused by an electrochemical corrosion cell developed by a potential difference in the metal that makes one part of the cell an anode, and the other part of the cell the cathode. Different metals have different potentials in the same electrolyte. This potential difference is the driving force, or the voltage, of the cell. As with any electrochemical corrosion cell, if the electrolyte is continuous from the anode to the cathode and there is a metallic path present for the electron, the circuit is completed and current will flow and electrochemical corrosion will occur.

VI.12.1. Galvanic cathodic protection

Corrosion of Reinforcing Steel and the Evolution of Cathodic Protection Systems: The corrosion of reinforcing steel embedded in concrete gives rise to a variety of problems such as tensile stresses that cause cracking and spalling of concrete, a low alkaline environment that leads to the breakdown of the passive oxide layer on the steel which accelerates corrosion rates and reduces structural integrity, a high porosity surface layer of rust with a higher volume than steel and a cathodic reaction that consumes OH ions supplied by the cement matrix causing a gradient in the pH between the anode and cathode [2].

As steel reinforcement is a further component in ferrous-based concrete systems, it is possible for a galvanic cell corrosion to develop between the surface of the concrete and the reinforcing steel particle leading to the eventual production of delamination and in turn rendering the concrete system susceptible to a variety of other forms of corrosion. Alternatively, if it is expected that the mesh will be used as a sacrificial anode to prevent corrosion of the mild steel mounted clip, the feasibility of attachments requiring a smaller number of joints will be assessed. Principles of Cathodic Protection: The term "cathodic protection (CP)" denotes a leading electrochemical technique for the mitigation of corrosion damage, particularly of steel-reinforced concrete (SRC) structures, increasingly recognized as one of the most powerful tools in the fight against climate changes and that enables the correction, protection and the maintenance of all structures and equipments subjected to construction and building regulations. In cathodic protection of the steel in reinforced concrete structures, the negative shift in the potential of the cathode determines the effectiveness of the protection from corrosion where the cathode potential is depressed relative to the electrolyte.

This negative shift in the cathode potential occurs by two mechanisms: the depressurization of the cathode potential relative to the electrolyte and the elevation of the potential of the electrolyte in the vicinity of

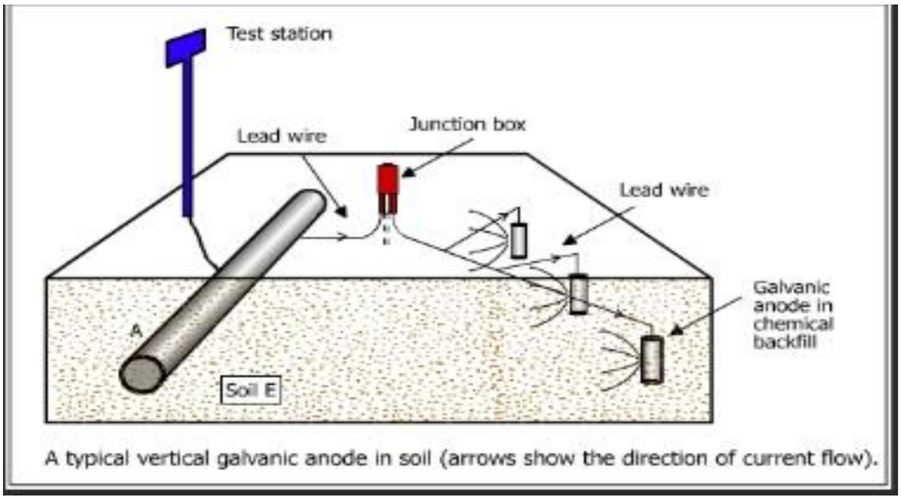

Figure VI.8 : Galvanic cathodic protection

In galvanic anode systems, the current required for cathodic protection is supplied by the corrosion of an active metal. Sacrificial anode systems depend upon the differences in corrosion potential that are established by the corrosion reactions that occur on different metals or alloys. For example, the natural corrosion potential difference of iron referenced to a copper/copper sulfate reference electrode is commonly found to be between -0.4 and -0.6 volts DC. The natural corrosion potential of zinc referenced to a copper/copper sulfate reference electrode is about -1.1 volts. Thus, if the two metals are electrically connected, the potential difference between the iron and the zinc is approximately 0.5 to 0.7 volts DC, and the corrosion of the zinc becomes the source of current and prevents corrosion of the iron cathode. This is illustrated in Figures IV.8 and IV.9. Zinc, magnesium, and aluminum alloys all have potentials that are sufficiently more negative than iron or steel and may be useful for the protection of those structures in many environments. Other metals such as copper and copper alloys have a lower potential than iron or steel and are easily protected by steel (and many other metals). Materials such as aluminum alloys that have a higher potential than iron or steel are more difficult to protect, but even aluminum alloys can be effectively protected by magnesium alloys or commercially pure magnesium. In the process of providing electrons for the cathodic protection of a less active metal, the more active metal (anode) corrodes.

The more active metal (anode) is sacrificed to protect the less active metal (cathode). The amount of corrosion is dependent on the metal being used as an anode and is directly proportional to the amount of current supplied. Another factor is the anode efficiency, which accounts for the anode's self-corrosion rate and the corrosion rate for the amount of cathodic protection current. To provide a uniform electrolyte around an anode in soil, maintain moisture, and lower the resistance of anode-to-earth, a special backfill is used.

This backfill is normally 75 percent gypsum, 20 percent bentonite, and 5 percent sodium sulfate. The anodes in galvanic cathodic protection systems must be periodically inspected and replaced when consumed. In many cases, when the sacrificial anodes have failed, the entire system is replaced with an impressed current system. Sacrificial anode cathodic protection systems are fundamentally very simple. The simplest systems consist of an anode fabricated from an active metal such as zinc that is directly connected to the structure in an area where it will be exposed to the same environment as the structure being protected. This type of system is widely used in the protection of ships and waterfront structures

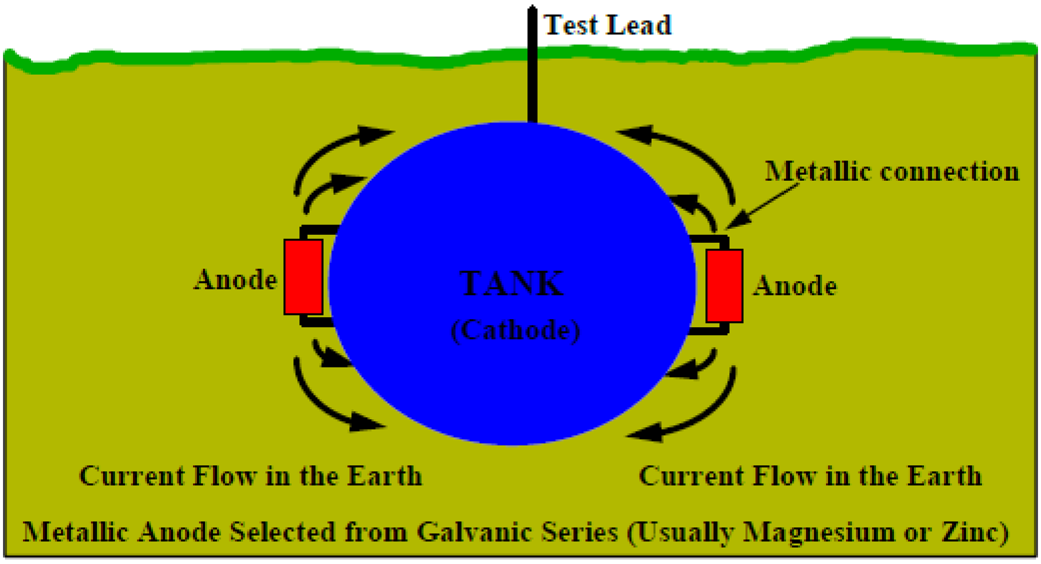

Figure VI.9 : Direct Attachment Galvanic (Sacrificial) Cathodic Protection System

For the protection of underground structures such as pipelines, the anodes are not usually attached directly to the structure, but are placed in the soil, evenly distributed a short distance from the pipeline, and are connected to the pipeline by a wire, usually through a test station. This type of sacrificial anode system is shown in Figure VI.10. The application of galvanic anodes is limited by the small potential difference (normally less than 1 volt DC) that can be obtained. Galvanic systems generally can only be economically used on small or well-coated structures in low resistivity electrolytes. Available voltage and estimated output of various sacrificial anodes in different resistivity electrolytes. Since the amount of cathodic protection is dependent on the current density supplied to the protected structure, the electrolyte resistivity determines the amount of current that the limited voltage will supply.

The amount of metal exposed to the electrolyte determines the amount of current required. Uncoated (bare) structures may require an exorbitant number of anodes for adequate protection. In higher resistivity electrolytes, the small anode-structure voltage difference would yield (Ohms law) an extremely small amount of anode current, hence requiring a large amount of anodes. High puritymagnesium anodes have the highest potential available, but in high resistivity soil there would not be sufficient current to protect a structure unless it had a very good coating

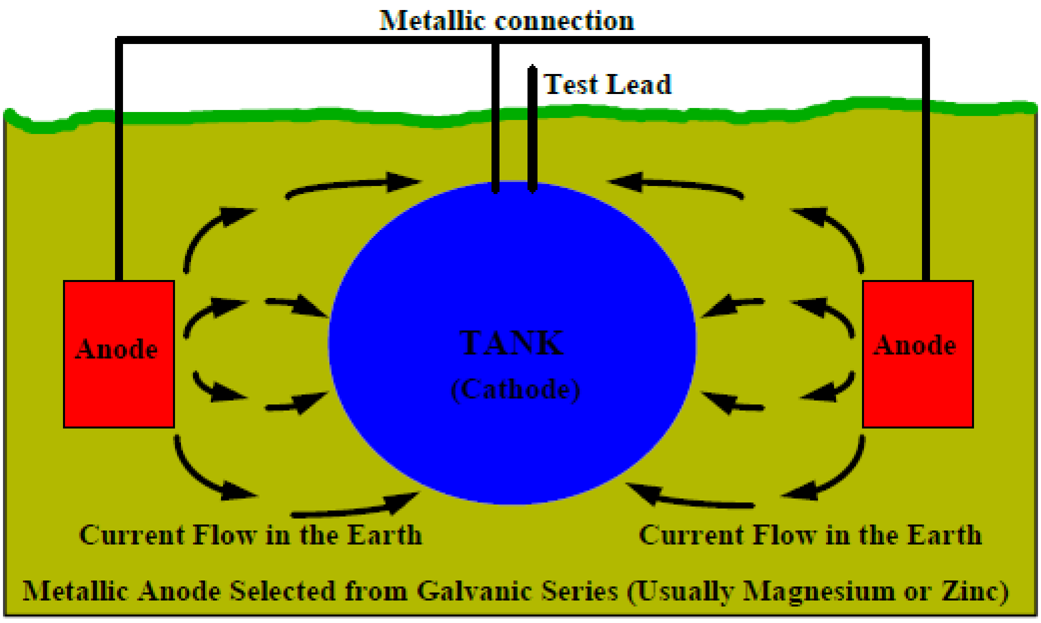

Figure VI.10 : Distributed Sacrificial (Galvanic) Cathodic Protection System

VI.13. Integration of cathodic protection in asset management strategies

The increase in the number of reinforced and pre-stressed concrete structures has led to a corresponding increase in the problem of steel corrosion in such structures. Steel corrosion in reinforced concrete structures results in reduction in strength and ductility and enhanced then cracking of concrete. Moreover similar effect has been found by using pre-stressed concrete structures for post-tension. [12] presented an analysis of the mechanism of corrosion and the modes of corrosion failures in steel framed masonry structures. The theory predicts the corrosion rate of steel and the fatigue life of the steel masonry connections without corrosion. Cathodic protection was introduced for the repair and restoration of steel masonry structures; the geometry and modes of corrosion failures are specified; and a method of protection is selected based on theoretical prediction and testing of corrosion rate and fatigue life. A grate advantage of the cathodic protection applied in this manner is that the protection is effected with minimal damage to the structure Functions of the protection materials and equipments are: (1) To determine the geometry and the mode of the corrosion failures, (2) to design and install the protection materials and equipment, (3) to resolve practical problems involved in establishing satisfactory protection operation.

VI.14. Training and certification programs in cathodic protection

VI.14. 1. The purpose

The information and items contained in this standard are intended to be used by training providers in the development, management, and administration of training and certification programs for cathodic protection personnel. Upon the establishment of training and certification programs, certification may be undertaken according to the requirements of General Principles of Cathodic Protection of Buried or Immersed Onshore Metallic Structures Using Sacrificial Anodes; General Principles of Cathodic Protection of Buried or Immersed Onshore Metallic Structures Using Impressed Current; General principles of cathodic protection are dealt with in these documents. Utilisation d'Anodes Fusibles; Protection Cathodique des Structures en Acier Enterrées ou Immergées en Onshore. Restauration; Cathodic protection. Pipelines. Alternative current interference; Cathodic Protection of Pipeline Systems. Part 1: On-land Pipelines; Guide on the Influence of High Voltage AC Power Systems on Metallic Pipelines; Cathodic Protection against Corrosion on Steel in Concrete; Cathodic Protection of Steel in Reinforced Concrete Corrosion engineering. Energy Transmission and Distribution Guidance on rectifier CP systems for tanks. Cathodic Protection of above ground petroleum storage tanks. Part 1: general considerations regarding costs. Protection cathodique contre la corrosion en acier dans le béton; Macrocell and localised corrosion. General principles; Corrosion of metals and alloys—Determination of AC corrosion. Protection criteria Scope; General Corrosion Information; Fundamentals of Corrosion; Rules for CP Training and Certification Programs; Rules for CP Training Programs for Engineers Near AC Railways; Rules for CP Training Programs for Other Individuals near AC Systems. are dealt with in this document. Basic theory; Corrosion of metals and alloys; Voltage gradients in soil and AC voltage effects on CP systems; Induced AC voltage gradient on pipelines by HVAC networks; Effects of Soil Resistivity; Effects of AC on Steel; Proximity effect; The risk from low level AC and step potentials; Amplified effects observed in CP systems; Mitigation; Conclusions; Arrangement on system earthing of AC substation and the connected high voltage AC system; Management of alternating current on electrical installations; Fault and maintenance currents and disturbances; Arcing effects; Voltage distributions; Speed of operation and interlocks; Effect of high phase order tripping on HV lines; Earthing of electrical and associated electronic devices; Mitigation for new substations; Mitigation for existing facilities; De-energisation of steel; Discussion on 'High AC Fault Currents in a Substation'; Discussion on 'Casestudies of AC Corrosion on Buried Pipelines in Europe'; Discussion on 'Effect of Alternating Current by High Power Lines Voltage and Electric Transmission Systems in Pipelines Corrosion'; Discussion on 'AC Corrosion of Pipelines Associated With AC Traction Systems'; Discussion on 'Observations of Complex AC-Related Corrosion Damage'; Discussion on 'AC Corrosion Experienced by a European Natural Gas Grid'; alternated; Mitigation of Alternating Current and Lightning Effects on Metallic Structures; Current/grounding systems on HV towers; Current/grounding systems on steel lattice forest; Overview of mitigation measures; Transmission towers with Faraday cage for protection of voltage based systems; Capacitance effect of power lines on pipelines; Maintenance and operating condition of current/grounding systems and pipelines annotated for possible AC fault current; Damage to protective Areas; Protection zones, cables and protection measures; To Do list; Irrational measures; Alternative measures can be taken with DOMINO effect; Buildings close to railway EM grids.

VI.14.2. International collaborations and research initiatives in cathodic protection

Cathodic protection (CP) is a technique used to control the corrosion of a metal surface by making it the cathode of an electrochemical cell. CP underground piping, storage tanks, water storage tanks, ships, submarines, offshore pipelines, and production platforms protect such structures from ocean, brackish water, saline mud, and soil-core corrosion. Cathodic prevention can retard the rate of corrosion by addressing it at source and prevent subversive rust from developing and endangering the concrete cover layer of the steel reinforcement bar. Future research focuses on increasing the service life prediction by enhancing electrochemical models of impressed current cathodic protection. The key issue concerns improving the interest at the international level of the research results in order to foster the participation of the industrial actors providing the data for modeling at this scale. Besides, a preliminary comparison between the experimental results of the different partners has demonstrated the need to agree on a strict procedure for data acquisition and harmonic analysis of the electric field and of the effects on the pipeline [4].

VI.14.3. Conclusion and future directions in cathodic protection research

This book presents overviews on the principles and applications of cathodic protection in corrosion prevention. Cathodic protection works by supplying an electrical current reaction that reduces the rate of anodic corrosion reactions on a metal. Applying a slight electrical potential to the metal in relation to the oxidizing environment reduces the driving force for the anodic reaction, slowing the formation of corrosion, and reducing the susceptibility of the metal to oxidize. There are primarily two types of cathodic protection—anode and cathode—these are often passive, as they involve adding a metal that can act as the anode or cathode for the corroding metal [9]. However, in practice most industrial installations are active cathodic protection, and this is what is referred to in the book. In active cathodic protection, the electric current is supplied from an external source, and it can either be supplied as a direct current, or as an alternating current fed through a transformer, with the low voltage output supplied to the metal.

Starting from these basic principles, new directions in cathodic protection, both commercially and through research have been considered in order to try to improve the technology further. Some of the main areas of new development have been within understanding the fundamental process of cathodic protection, such as coating or oxygen transport. However at this level the principles of cathodic protection are now fairly well understood. One of the most recent experiments has been work considering the design alternatives for cathodic protection systems, and ways in which the economics of such systems can be evaluated. There is a growing trend to consider cathodic protection in the design stages of a structure, rather than as a simple process to mitigate corrosion once the structure has been built. This requires a more sophisticated understanding of the corrosion process, and advances in this area are frequent, as are related advances in the modeling of processes such as the current and potential distribution in a structure subjected to cathodic protection.

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CHAPTER VII

ANODIC PROTECTION

CHAPTER VII : Anodic protection

VII.1. Introduction

In contrast to cathodic protection, anodic protection is relatively new. Edeleanu first demonstrated the feasibility of anodic protection in 1954 and tested it on small-scale stainless-steel boilers used for sulfuric acid solutions. This was probably the first industrial application, although other experimental work had been carried out elsewhere. This technique was developed using electrode kinetics principles and is somewhat difficult to describe without introducing advanced concepts of electrochemical theory. Simply, anodic protection is based on the formation of a protective film on metals by externally applied anodic currents. Anodic protection possesses unique advantages. For example, the applied current is usually equal to the corrosion rate of the protected system. Thus, anodic protection not only protects but also offers a direct means for monitoring the corrosion rate of a system. As an enthusiast and famous corrosion engineer claimed, “anodic protection can be classed as one of the most significant advances in the entire history.

Anodic protection can decrease corrosion rate substantially. Table 7. 1 lists the corrosion rates of austenitic stainless steel in sulfuric acid solutions containing chloride ions with and without anodic protection. Examination of the table shows that anodic protection causes a 100,000- fold decrease in corrosive attack in some systems. The primary advantages of anodic protection are its applicability in extremely corrosive environments and its low current requirements.2

Table 7.2 lists several systems where anodic protection has been applied successfully Anodic protection has been most extensively applied to protect equipment used to store and handle sulfuric acid. Sales of anodically protected heat exchangers used to cool H2SO4 manufacturing plants have represented one of the more successful ventures for this technology.

TABLE VII.1 : Anodic Protection of S30400 Stainless Steel Exposed to an Aerated Sulfuric Acid Environment at 30°C with and without Protection at 0.500 V vs. SCE

Acid concentration, M	NaCl, M	Corrosion rate, $\mu m \cdot y^{-1}$ Unprotected	Protected
0.5	10^{-5}	360	0.64
0.5	10^{-3}	74	1.1
0.5	10^{-1}	81	5.1
5	10^{-5}	49,000	0.41
5	10^{-3}	29,000	1.0
5	10^{-1}	2,000	5.3

Table VII.2 : Current requirements for anodic protection

H_2SO	Temperature, °C	Alloy	Current density: To passivate, $mA \cdot cm^{-2}$	To maintain, $\mu A \cdot cm^{-2}$
1 M	24	S31600	2.3	12
15%	24	S30400	0.42	72
30%	24	S30400	0.54	24
45%	65	S30400	180	890
67%	24	S30400	5.1	3.9
67%	24	S31600	0.51	0.10
67%	24	N08020	0.43	0.9
93%	24	Mild steel	0.28	23
99.9% (oleum)	24	Mild steel	4.7	12
H_3PO_4				
75%	24	Mild steel	41	20,000
115%	82	S30400	3.2×10^{-5}	1.5×10^{-4}
NaOH				
20%	24	S30400	4.7	10

These heat exchangers are sold complete with the anodic protection systems installed and have a commercial advantage in that less costly materials can be used. Protection of steel in H2SO4 (_ 78% concentration) storage vessels is perhaps the most common application of anodic protection. There is little activity directed toward developing applications to protect metals from corrosion by other chemicals.3 Anodic protection is used to a lesser degree than the other corrosion control techniques, particularly cathodic protection. This is mainly because of the limitations on metal-chemical systems for which anodic protection will reduce corrosion. In addition, it is possible to accelerate corrosion of the equipment if proper controls are not implemented. However, anodic protection has its place in the corrosion control area, provided some important basics are respected.

VII 2. Passivity of metals

The passivation behavior of a metal is typically studied with a basic electrochemical testing setup (App. D, Basic Electrochemical Instrumentation). When the potential of a metallic component is controlled and shifted in the more anodic (positive) direction, the current required to cause that shift will vary. If the current required for the shift has the general polarization behavior illustrated in Fig. 7.1, the metal is active-passive and can be anodically protected. Only a few systems exhibit this behavior in an appreciable and usable way. The corrosion rate of an active-passive metal can be significantly reduced by shifting the potential of the metal so that it is at a value in the passive range shown in Fig. 7.1. The current required to shift the potential in the anodic direction from the corrosion potential *E*corr can beseveral orders of magnitude greater than the current necessary to maintain the potential at a passive value. The current will peak at the passivation potential value shown as *E*pp (Fig. 7.1). To produce passivation the critical current density (*i*cc) must be exceeded. The anodic potential must then be maintained in the passive region without allowing it to fall back in the active region or getting into the transpassive region, where the protective anodic film can be damaged and even break down completely. It follows that although a high current density may be required to cause passivation (_ *i*cc), only a small current density is required to maintain it, and that in the passive region the corrosion rate corresponds to the passive current density (*ip*). The relative tendency for passivation is strongly dependent on the interactions between a metal and its environment. The passivation behavior can vary extensively with changes in either. Figure VII.2 illustrates how the sensitization of a S30400 stainless steel, for example, can affect its passivation behavior when exposed to sulfuric acid.4

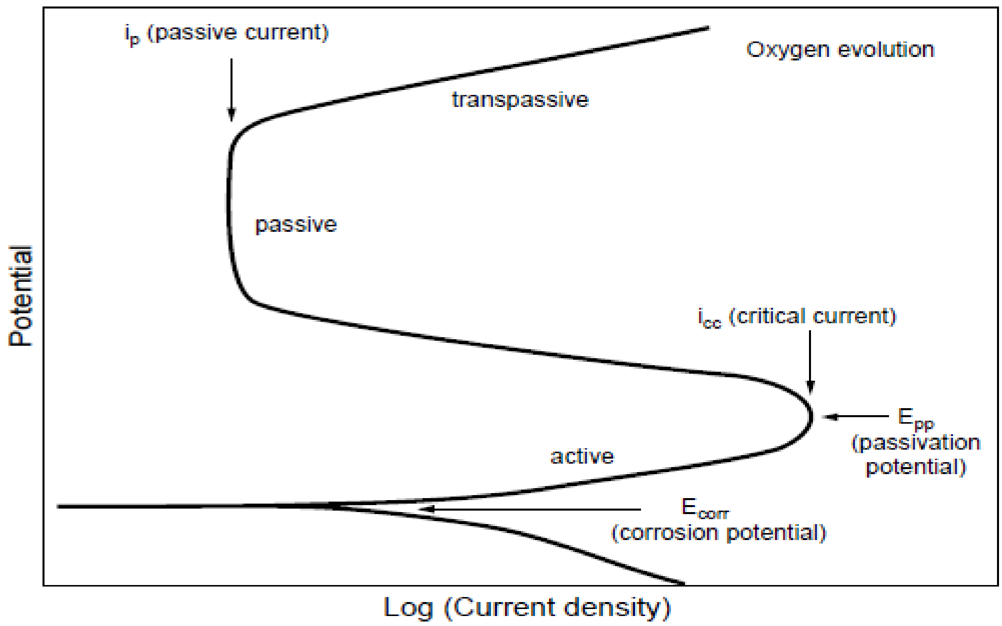

Figure VII.1 : Hypothetical polarization diagram for a passivable system with active, passive, and transpassive regions

Among the parameters that are particularly affected by sensitization are *ip* and *i*cc, as defined in Fig. 7.1. In this example, the ability to sustain passivity increases as the current density to maintain passivity (*ip*) decreases and as the total film resistance increases, as indicated from measurements obtained with different metals exposed to 67% sulfuric acid (Table 7.3). The lower or more reducing the potential at which a passive metal becomes active, the greater the stability of passivity. The depassivation potential corresponding to the passive-active transition, called the Flade potential, can differ appreciably from *E*pp measured by going through the active-passive process of the same system.

This technical distinction is important for the control aspect of anodic protection where *E*pp is the potential to traverse to obtain passivation, and the Flade potential is the potential to avoid traversing back into active corrosion. Passivity can also be readily produced in the absence of an externally applied passivating potential by using oxidants to control the redox potential of the environment. Very few metals will passivate in nonoxidizing acids or environments, when the redox potential is more cathodic than the potential at which hydrogen can be produced. A good example of that behavior is titanium and some of its alloys, which can be readily passivated by most acids, whereas mild steel requires a strong oxidizing agent, such as fuming HNO3, for its passivation. Alloying with a more easily passivated metal normally increases the ease of passivation and lowers the passivation potential, as in the alloying of iron and chromium in 10% sulfuric acid (Table 12.4

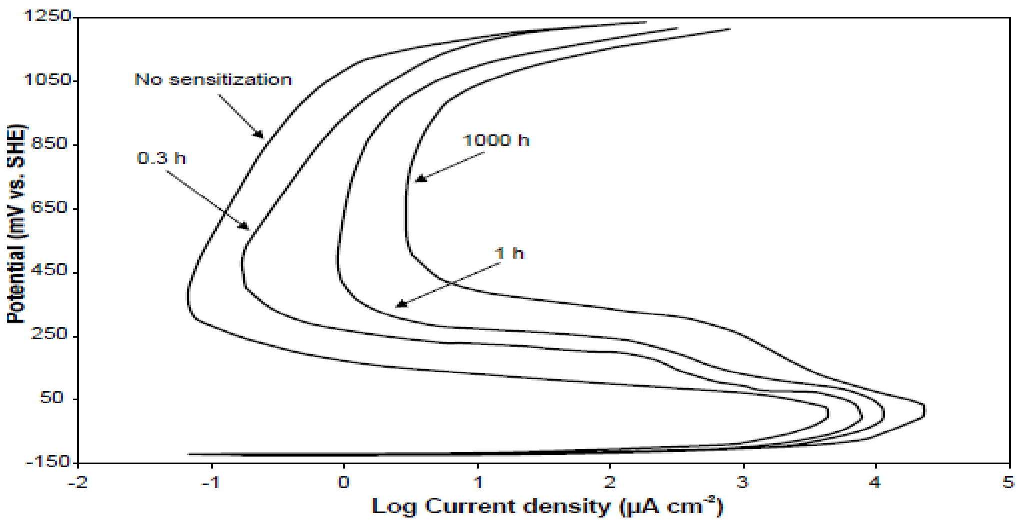

Figure VII. 2 : Anodic polarization curves of S30400 steel in a 1 M H_2SO_4 at 90°C after sensitizationfor various times

Small additions of copper in carbon steels have been found to reduce *ip* in sulfuric acid. Each alloy system has to be evaluated for its own passivating behavior, as illustrated by the case

Ni-Cr alloys where both the additions of nickel to chromium and chromium to nickel decrease the critical current density in a mixture of sulfuric acid and 0.25 *M* K2SO4 (Table 7.5).1

The parameters defining and controlling the passivation domain of a system are thus directly related to the composition, concentration, purity, temperature, and agitation of the environment. This is illustrated with the current densities required to obtain passivity (*i*cc), and to maintain passivity (*ip*), for a S30400 steel in different electrolytes, as presented in Table 12.6. From the data in this table, it can be seen that it is approximately 100,000 times easier to passivate large areas of this steel in contact with 115% phosphoric acid than in 20% sodium hydroxide. The concentration of the electrolyte is also important, and for a S31600 steel in sulfuric acid, although there is a maximum corrosion rate at about 55%, the critical current density decreases progressively as the concentration of acid increases (Table 7.7).1

TABLE VII..3 : Current Density to Maintain Passivity and Film Resistance of Some Metals in 67% Sulfuric Acid

Metal or alloy	i_p, μA·cm^{-2}	Film resistance, MΩ·cm
Mild steel	150	0.026
S30400 steel	2.2	0.50
S31000 steel	0.5	2.1
S31600 steel	0.1	17.5
Titanium	0.08	1.75
N08020	0.03	4.6

TABLE VII.4 : Effect on Critical Current Density and Passivation Potential of Chromium Content for Iron-Chromium Alloys in 10% Sulfuric Acid

Chromium, %	i_{cc}, mA·cm^{-2}	E_{pp}, V vs. SHE
0	1000	+0.58
2.8	360	+0.58
6.7	340	+0.35
9.5	27	+0.15
14.0	19	−0.03

TABLE VII.5 : Effect on Critical Current Density and Passivation Potential on Alloying Nickel with Chromium in 0.5 *M* and 5 *M* H2SO4 Containing 0.25 *M* K2SO4

Ni, %	i_{cc}, $mA{\cdot}cm^{-2}$		E_{pp}, V vs. SHE	
	0.5 *M*	5 *M*	0.5 *M*	5 *M*
100	100	23	+0.36	+0.47
91	0.95	3.9	+0.06	+0.14
77	0.11	0.82	+0.07	+0.08
49	0.020	0.20	+0.03	+0.06
27	0.012	0.041	+0.02	+0.05
10	0.0013	0.011	+0.04	+0.08
1	1.0	5.0	−0.32	−0.20
0	1.5	8.0	−0.30	−0.20

The presence in the environment of impurities that retard the formation of a passive film or accelerate its degradation is often detrimental. In this context, chloride ions can be quite aggressive for many alloys and particularly for steels and stainless steels. As an example, the addition of 3% HCl hydrochloric acid to 67% sulfuric acid raises the critical current density for the passivation of a S31600 stainless steel from 0.7 to 40 mA_cm_2 and the current density to maintain passivity from 0.1 to 60 _A_cm_2. Therefore, the use of the calomel electrode in anodic-protection systems is not recommended because of the possible leakage of chloride ions into the electrolyte.

CHAPTER VIII

ORGANIC COATINGS

CHAPTER VIII: Organic coatings

VIII.1. Introduction

Although coatings have been used for over thousands of years for decorative and identificationpurposes, the industrial importance of coatings has only been recognized after World War II. The total amount of paint sold annually amounts to billions of gallons. In 2000, USA alone manufactured about 3.5 billion gallons of paint. About one-third of the production of paint is used to protect and decorate metal surfaces. All forms of transport, such as trains, ships, automobiles, aeroplanes, underground buried structures, such as tanks, oil and gas pipelines, offshore structures, iron and structures and all metallic equipment require the use of coatings. The coating industry has, therefore, turned out to be one of the largest in terms of production. The importance of coating can be judged from the fact that coating can hardly be ignored in any corrosion protective scheme.

Corrosion protection of over-ground and underground structures by protective coatings is one of the most proven methods. Other methods include cathodic protection, environmental modification, material selection and design. In contrast to the behavior of rust on steel, the formation of an oxide affords protection against corrosion. If the resistivity of electrolyte is increased and the electron flux is retarded, the rate of corrosion is decreased. By applying coatings of high resistivity, such as epoxies, vinyls, chlorinated rubbers, etc. the flow of electric current to the metal surface is impeded. Also, the higher the thickness of the coating, the higher would be the electrical resistance of the coating. Amuchhigher resistance to the current flow would, therefore, be offered. Thus increasing the electrical resistance of metals by coating offers an excellent method of corrosion prevention. Another method to prevent corrosion is by the use of inhibitors. This can be achieved by using inhibitive pigments, like zinc chromate, red lead and zinc phosphate in coatings. An alternative method is to use a metal more anodic than iron, such as zinc. This is done by using zinc-rich paints. The zinc etal prevents the corrosion of iron by releasing electrons into the iron surface. Thus, coating is an effective method to control corrosion. Coatings must have the following characteristics for good corrosion resistance:

(a) a high degree of adhesion to the substrate

(b) minimumdiscontinuity in coating (porosity)

(c) a high resistance to the flow of electrons

(d) a sufficient thickness (the greater the thickness, the more the resistance)

(e) a low diffusion rate for ions such as Cl^- and for H_2O.

Coating and paint technology is adapting to the environmental requirements. The development of water-borne coatings and solvent-free coatings signify new health and safety trends in coating technology.

VIII.2. Coatings and coating processes

Coating fundamentals makes reference to a multitude of concepts and properties. A critical property of antifouling paint is, for example, the inhibition of living organism growth on the coating. A fire-resistant coating, on the other hand, should resist or retard the burning of the substrate. From a corrosion point of view a coating is rated on the resistance it provides against corrosion in a specific environment, and because there are many variations in environment corrosivity, there is also a great variety of corrosion protective coatings. These can be broadly divided into metallic, inorganic, and organic coatings. A general description of how the main elements are used in metallic and inorganic coatings is given in Table VIII.1

Objectives

The following are the objectives of coatings:

(1) Protection of equipment and structures from the environment by acting as a barrier between the substrate and the aggressive environment, such as the marine and industrial environments.

(2) Control of solvent losses.

(3) Control of marine fouling; certain constituents in coating control the growth of mildew and marine fouling in seawater.

(4) Reduction in friction; coating reduces friction between two contacting surfaces.

(5) Pleasant appearance; certain types of coatings provide a pleasant appearance and roduce

attractive surroundings.

(6) Change in light intensity; by selection of appropriate coatings the light intensity in rooms and buildings can be varied as desired.

(7) Visibility; many combinations of colors because of their visibility from large distances are used on TV and radio towers to warn aircraft.

(8) Modification of chemical, mechanical, thermal, electronic and optical properties of materials.

(9) Application of thin coatings on low-cost substrates results in increased efficiency and cost savings.

VIII.3. Classification of coatings

Coatings can be classified in the following categories according to corrosion resistance:

(a) Barrier coatings

(b) Conversion coatings

(c) Anodic coatings

(d) Cathodic coatings.

VIII.3.1. Barrier coatings

Barrier coatings are of four types – anodic oxides, inorganic coatings, inhibitive coatings and organic coatings.

(1) Anodic Oxides

Alayer of Al_2O_3 is produced on aluminum surface by electrolysis. As the oxides are porous, they are sealed by a solution of potassium dichromate. The object of sealing is to minimize porosity. However, chromates have health hazards and are not allowed in some countries.

(2) Inorganic Coatings

These include coatings like ceramics and glass. Glass coatings are virtually impervious to water. Cement coatings are impervious as long as they are not mechanically damaged.

(3) Inhibitive Coatings

In several instances, inhibitors are added to form surface layers which serve as barriers to the environment. Inhibitors, like cinnamic acid, are added to paint coatings to prevent the corrosion of steel in neutral or alkaline media.

(4) Organic Coatings

Epoxy, polyurethane, chlorinated rubber and polyvinyl chloride coatings are extensively used in industry. They serve as a barrier to water, oxygen, and prevent the occurrence of a cathodic reaction beneath the coating. The barrier properties are further increased by addition of an inhibitor, like chromate in the primer

VIII.3.2. Conversion coatings

Phosphate and chromate coatings are examples of conversion coatings. Conversion coatings are so-called because the surface metal is converted into a compound having the desired porosity to act as a good base for a paint. If iron phosphate is used, the following reaction takes place:

$$2\ Fe + 3\ NaH_2PO_4 \longrightarrow 2\ FeHPO_4 + Na_3PO_4 + \uparrow H_2 \longrightarrow \textbf{Coating}$$

The corrosion resistance is enhanced by phosphating

VIII.3.3. Anodic coatings

By anodic coating, it is meant that a coating which is anodic to the substrate, such as zinc aluminum or cadmium coatings. On steel such coatings are generally called sacrificial coatings. They protect the substrate at the expense of the metallic coating applied. The zinc coatings protect the substrate by acting as a sacrificial anode for the steel which is cathodic to zinc:

$$E^\circ_{Zn} = -0.763\ V,\ E^\circ_{Fe} = -0.44\ V$$

Any breaks in the coating cause the anodic oxidation of Zn to occur.

$$Zn \longrightarrow Zn^{2+} + 2\ e^-$$

The electrons are consumed by the iron substrate which acts as a cathode. The potential is made more negative by electrons and a cathodic reaction is forced to occur on it.

$$2H^+ + 2e^- \longrightarrow H_2 \uparrow$$

A fine film of H_2 is formed on the surface. The steel being cathodic does not corrode. Thus, by acting as a sacrificial material, zinc corrodes while the steel substrate is protected.

VIII.3.4. Cathodic Coatings

In this type of coating, the metals which are deposited are electropositive to the substrate. For instance, for copper coated steel, copper **(E° = + 0.337 V)** is positive to steel **(E° = − 0.440 V)**.

The coatings must be pore-free and thick. Electroplated coatings are generally pore-free and discontinuities are not observed. However, if the coating contains a flaw (crater), it acts as the anode with respect to the substrate. Consequently, electrons flow from the crater to the noble coating. At the crater, hydrogen is evolved.

$$2H^+ + 2e \rightleftarrows H_2 \uparrow$$

Often an intermediate layer is put in between the substrate and the noble coating, such as the nickel–chromium coatings. Consider nickel coating on a steel substrate. A layer of bright nickel is laid on the dull layer of nickel. Over the bright nickel a layer of chromium is laid. The bright nickel (high sulfur content) is more noble than the steel substrate. Such a coating system is called duplex coating.

VIII.3.5. Miscellaneous coatings

These include glass coatings, porcelain coatings and high-temperature coatings.

VIII.4. Scope of coatings

Sky is the limit for the coating market. The following are the major target areas:

■ Aerospace, power plants (turbines) and aircraft.

■ Oil and mining industry. Equipment, such as pumps, valves, drilling rigs, slurry pumps,

■ Information storage: discs (magnetic coatings), TV display systems.

■ Desalination plants: brine heaters, heat exchangers, circulation pumps, valves, etc.

■ Automotive industry: gears, valves, pistons, panels, etc.

■ Solar energy: photovoltaic cells and solar cells.

■ Biotechnology and surgical implantation: artificial hearts, valves and joints.

■ Utilities: all household appliances, washing machines, kitchenware and all electrical appliances.

■ Pipelines: oil, gas and utilities pipelines.

■ Transportation: decks, bridges and railcars.

VIII.5. Painting, coating and lining

(a) A *paint* is a pigmented liquid composition containing drying oils alone or drying oils in combination with resins which combine with oxygen to form a solid protective and adherent film after application as a thin layer.

(b) A*coating* is any material composed essentially of synthetic resins or inorganic silicate polymers which forms a continuous film over a surface after application and is resistant to corrosive environments.

(c) A*lining* is essentially a film of material applied to the inner surface of a vessel or pipeline designed to hold the liquids or slurries. with oxygen to form a solid protective and adherent film after application as a thin layer.

(b) A*coating* is any material composed essentially of synthetic resins or inorganic silicate polymers which forms a continuous film over a surface after application and is resistant to corrosive environments.

(c) A*lining* is essentially a film of material applied to the inner surface of a vessel or pipeline designed to hold the liquids or slurries.

VIII.6. Paint coating system

The coating system comprises:

(a) The primer

(b) The intermediate coat

(c) The top coat

The primer is the most important component of the coating system as the rest of the coating is applied on the primer. In many paint systems, such as those containing a good proportion of natural oils, the pigments may be inhibitive. However, some pigments, such as red lead in linseed oil (red lead primer) react with the oil to produce soap and protect the steel surface although they do not act inhibitively. The following are the functions of primers:

(1) It must be strongly bonded to the substrate.

(2) It must be resistant to corrosive environments and suppress corrosion.

(3) It must provide good adhesion to the intermediate coat or the top coat. Primers are allowed to stand for a sufficiently long length of time before any coating is applied. Primers can be inhibitive, impervious or cathodic, as described below, and their applications are dependent on the environment encountered by the metallic structure.

(1) Inhibitive Primers

The pigment contained in the primer reacts with absorbed moisture in the coating and form a passive surface on the substrate, such as steel. Pigments, such as chromate salts and red lead are the examples of inhibitive pigments, but have health hazards.

(2) Impervious Primer

This primer used in impervious coating systems makes the coating much more impervious to the passage of CO2, oxygen, air, ions and electrons. Conventional thin film coatings cannot prevent oxygen and water permeation. The primer in an impervious system is used with a thick coal tar enamel to form a highly impervious coating. The pigments are generally metal salts, chromates of zinc, lead and strontium, but Cr and Pb contents have health hazards.

(3) Cathodically Protective Primer

One good example is a primer containing zinc. As zinc is anodic to steel, zinc corrodes in preference to steel and protects the steel from corrosion. Experience has shown that a zinc-rich primer can double the life of a chlorinated rubber or an epoxy top coat. The three types of primers described above form the basis of three important coating systems:

(a) impervious coating system for equipment requiring immersion,

(b) inhibitive system for application in marine atmosphere and

(c) cathodically protective system for severe corrosive environments.

VIII.7. Paint coating components

(a) Vehicle. This is the liquid portion of the paint in which the pigment is dispersed. It is composed of *binder* and the *solvent* or *thinner* or both.

(b) Binder. This binds the pigments in the coating in a homogeneous film. The binder also binds the total coating to the substrate. The binders provide the basis for the generic terminology of paint. The physical and chemical properties of paints are determined by the binders.

(c) Pigment. A pigment not only provides a pleasing color but protects the binder from the adverse effect of ultraviolet radiation on the coating.

(d) Solvent. The purpose of the solvent is to provide the surface with a coating material in a form in which it can be physically applied on the surface.

(e) **Additives**. These are used to modify the properties of the coating, such as reducing drying time and enhancing the desired properties. One example is a *plasticizer* which makes the film flexible. Similarly a *drier* may be added. It is a substance, such a compound of lead, manganese, hich when introduced in drying oils reduce their time. A drying oil, such as tung oil, forms a tough solid film in air.

(f) Extenders. They are added to improve the application properties of the paint. Table 7.1 summarizes the major components of paints. Paints and coatings can be divided into two categories: convertible type which need a chemical reaction, such as oxidation or polymerization, and the non-convertible type which are formed by evaporation of the solvents. The former category includes alkyds, epoxy, esters, polyesters, urethenes, silicon and other resins.

VIII.8. Composition and functions of paint

VIII.8.1. Coating components

There are several ways of classifying binders (resins). One such classification is given below:

(a) Drying oil types, such as alkyd

(b) Epoxy, polyurethane and coal tar (two-pack chemical resistance)

(c) Vinyl and chlorinated rubber (one-pack chemical resistance)

(d) Bituminous coatings

(e) Lacquers.

VIII.8.2. Alkyd resins

The alkyd resin is made through reacting an oil with an acid and alcohol. Alkyd resins are the most extensively used synthetic polymers in the coating industry. The principal raw materials are oils, fatty acids, polyhydric alcohols and dibasic acids. Examples of the above are:

(1) Oils – castor oil, soya bean oil, etc.

(2) Polyhydric alcohol (glycerol).

(3) Dibasic acid (phthalic acid).

VIII.8.3. Silicone Alkyds

There are numerous types of paints based on silicone which are combined either with alkyd or acrylic resin. Pure silicone resists temperature up to 600◦C and has excellent weathering properties. The copolymer is obtained by reaction between the hydroxyl groups in the alkyd resins with the hydroxyl groups in the silicon intermediates. The silicon intermediate has a low molecular weight. Silicone resin contains a relatively high percentage of reactive hydroxyl (Si – OH) or aloxyl (Si – OR) groups attached to silicon. Thus a copolymer structure is obtained which combines alkyd with silicone.

$$\mathbf{\equiv Si{-}OH + HOC{-}ALKYD \longrightarrow \equiv Si{-}O{-}C{-}ALKYD + H_2O}$$

The silicone intermediates commercially available for polymer modifications are

VIII.8.4. Metallic coatings

Metallic coatings provide a layer that changes the surface properties of the workpiece to those of the metal being applied. The workpiece becomes a composite material exhibiting properties enerally not achievable by either material if used alone. The coatings provide a durable, corrosion-resistant layer, and the core material provides the load-bearing capability. The deposition of metal coatings, such as chromium, nickel, copper, and cadmium, is usually achieved by wet chemical processes that have inherent pollution control problems. Alternative metal deposition methods have replaced some of the wet processes and may play a greater role in metal coating in the future. Metallic coatings are deposited by electroplating, electroless plating, spraying, hot dipping, chemical vapor deposition, and ion vapor deposition. Some important coatings are cadmium, chromium, nickel, aluminum, and zinc. Copper, gold, and silver are also used in electrical equipment and occasionally for specialty fastener applications. Copper is used as a base layer in multiple-plate electroplating, silver is used for antifretting purposes, and both silver and gold are sometimes used to provide electrical conductivity in waveguides and at contacts.

CHAPTER IX

METALLIC COATINGS

CHAPTER IX : Metallic coatings

IX.1. Introduction to metallic coatings

Metallic coatings have long been used in industry to improve the performance and longevity of products. These can take on many forms, such as the silver on mirrors, gold plating on jewelry, or the galvanized (zinc coated) steel used in construction, to name a few examples. Silvered glass mirrors added commercial uses in the 19th century, and automotive headlights with silvered reflectors were from about the 1900s, but it took some further years to begin using the mirror regularly as part of a motor vehicle. Gold coatings are often used over substances to enhance biocompatibility [1].

Zinc coatings gained importance as a way to protect steel from corrosion, with the rust formation of uncoated steel being a major issue in construction. Naturally, other materials are also used, like aluminum, to take advantage of various properties and decrease pinholes in the coating. Today, various other materials are used, and some coatings are made of a stack of different layers, each with a different function. This can mean, for example, that adhesion layers are first placed. Depending on the manufacturing process, a thin layer of nickel might be placed on a zinc-coated item to increase durability. In some applications, more layers of nickel or a third metal might be added on top [2].

In general, this will not be discussed in depth, just the properties and applications of base coatings. This is not something put into the coating, but a necessary property of the coating's structure and makeup. Layers can be applied in different ways. Galvanizing and electroplating are well-known means, but nowadays there is a large diversity of processes, with physical vapor deposition and chemical vapor deposition each having a number of possible techniques. There is some overlap, but for the sake of clarity this essay will attempt to address arrangements together. Obviously, localized or profile-specific coating techniques exist.

There are highly technological means to advance etching processes, making "film adhesion improvement of printing" a minor art form. It is also possible to purchase materials that reproduce the appearance of impossibly expensive solid metal items, such as dense woods with copper-plated grooves to give an almost flawless appearance. The interested reader is encouraged to research further amongst this extensive library of knowledge.

IX.2. Definition and types of metallic coatings

Metallic coatings are vital to increase productivity and reduce maintenance in various industries like acicularity, wear and corrosion resistance and to produce better quality products. These demands have driven the development of various technologies for metallic coatings. A metallic coating is an assembly of a metal to a metallic surface layer formed by electroplating, galvanization, or cladding. The main purpose of metallic coatings is to prevent corrosion, acid rain, abrasion and to improve the aesthetics, waterproofness, adhesive strength, wettability, and conductivity of non-metallic products.

Metallic coatings can be easily formed by dip coating, spray coating and pack cementation. There are 3 types of widely known and used methods for the formation of metallic coatings; Galvanizing (Galvanization), Electroplating (Plating) and Cladding.

Galvanizing is the process of coating iron or steel with a layer of zinc by immersing the metal in a bath of molten zinc. It occurs in 2 forms; Hot Dip Galvanizing and Electro Galvanizing. It is generally used for its rust resistance.

Electroplating refers to coating metals, ceramics or organic polymers with metals electrochemically. In this method, the metal to be coated is inserted into a chemical solution, and an electric current is passed through it. The current causes the ions in the solution to be deposited onto the chemically inactive metal. The preferred deposition metals are Cu, Zn etc.

Cladding refers to the method of coating a thick metal, which is less expensive than gold center with a desired metal, which is relatively expensive & generally with higher corrosion resistance or aesthetic value. There are 2 types of cladding according to field of use; Fusion Cladding and Roll Cladding. An example would be the roll cladding of aluminum on brass components to make them appear like 100% aluminum [1].

These 3 methods have different structures, properties, and applications of the coatings they produce. There are two characteristics which must be considered for the formation of high performance coatings; the thickness of the coating and the adhesive strength to the substrate. Additionally, the general features of the coatings like their structure, corrosion resistance, conductivity and overall aesthetic value are important. Thus, depending on conditions, one of these 3 different methods can be selected [3].

IX.3. Properties of metallic coatings

Effective coverage of metallic coatings depends on various properties. The performance of these materials can depend on the effectiveness of corrosion protection over a range of stressful environments [1]. First, universality in corrosion resistance explains why a considerable fraction of the U.S. coated products are developed to extend material life, given that most service conditions quickly degrade many common structural materials. Second, metallic coating can offer versatility impossible with other protective methods. Coatings have been successful in a wide range of end-use sectors, each with its properties that need to be optimized for cost-effectiveness. Besides general corrosion resistance, recent progress in the development of nano-composite coatings has prepared the way for metallic coatings that are highly resistant to wear [3]. Since 2000, a number of comparative studies on wear-resistant coatings have been published that present a quantitative analysis of the performance of coatings under anticipated service stress. The best coatings give a performance boost of at least an order of magnitude above the uncoated material. The work done in this area is used to explore critical issues in exposure methodologies and materials for the presentation of more recent results. To maximize versatility, a material form should aim to optimize certain material metallurgical features and, typically, involve distinct treatments before and during the exposure to oil the range of commercial coating were exposed to optimize stress and alloy-dependent media.

IX.3.1. Corrosion resistance

Corrosion resistance is a focal point in the discussion of metallic coatings, as it addresses one of the most prevalent challenges in materials' durability. It outlines the various ways in which coatings act as a barrier against corrosive media, such as moisture and salts. Attention is given to the different methods of improving corrosion resistance and the popular techniques, including alloying, dual-phase/double-layered coatings, painting/coating, and surface treatment; focusing on passivation, chromization, and anodization. Further, success stories in relevant industries are discussed, where metallic coatings have been effectively utilized addressing corrosion in real-world applications. A detailed economic study is described, showing the considerable potential for material cost saving with extended life spans due to effective corrosion prevention of underlying materials. Parameters and standards in defining corrosion resistance are outlined, in both qualitative and quantitative terms. A design guideline is provided so that engineers and decision-makers can adopt a suitable and cost-effective method of preventing corrosion in various environments [4].

IX.3.2. Wear resistance

Wear resistance is one of the most important properties of materials used in the presence of mechanical friction. Maintaining their geometry and proper shape directly depends on this feature. These conventional materials used in manufacturing sectors, mining industries, household equipment are continuously improved by developing new methods, high-performance materials, and thus, increasing efficiencies. Resistance to wear is usually achieved by providing a protective, hard surface which is protected from the material loss. The requirements of these protective surfaces were the starting point for the development of the coatings. The wear increases energy loss, as well as the shape error of the surface. The rate of wear is particularly high in uncoated surfaces. A high percentage of energy loss causes the material to lose its efficiency. Diverse coating methods have been developed to solve these problems. PVD, CVD, plasma, HVOF, laser, etc., are some of these methods. In all these processes, the coated surface is provided with the desired properties. Wear tests have been carried out on a surface that is not coated yet coated with a variety of methods to ensure the best efficiency of these methods. Improved efficiency was observed in all tested coatings, but the best coatings were observed in PVD coatings.

In mining and industrial sectors, material loss from increasing wear slows down production times and increases production costs. According to some studies, costs of 1 to 3% of GDP of the country are due to wear. Many equipment components used in the mines are removed from the expensive parts with the developing technology. Components that are susceptible to wear and erosion are coated with new methods and some components have been produced to have resistant to wear [3]. Fluid circles are made with hard metal coated plates. Hard metal coated silo plates with the Plasma method, which are prone to wear in UHDE natural gas plant storage area, have been used for 10 years and wear has been observed to decrease. Sintering furnaces are used to mix the ore particles with chemicals after breaking with rolls. The service life of the rolls used to give the torques on the sinter plates was doubled by the Cr_3C_2 coating technique [5]. Kurimexflux company Kaprol process equipment pieces are coated with WC-Co material and it is observed that the consumption is reduced by half. Coated bars were manufactured using different methods and materials, and higher wear resistance was shown in the PVD method. This was suggested to be more efficient in coated parts. CPU rod with SiC material with ELSYTAŞ cutting tip drilling results better than other drill bits. Minimum wear of rods and cutting tips was the reason for long life. Drilling could support itself without further damage. Drilling could be performed without support called "throwing" in a very short time, since the drill decreased very slowly. Since it is a coated tip, the drill does not decrease as much as possible and it also maintains its sharpness.

IX.4. Methods of applying metallic coatings

The methods of applying metallic coatings are pivotal in determining the effectiveness and suitability of the coatings. Various techniques used to apply metallic coatings may be grouped into wet and dry categories. In general, wet techniques involving liquid phases have an advantage in the deposition of thin films on polymer materials. Widely used wet techniques include electrolytic techniques such as electroplating, and techniques like PVD, CVD, thermal spraying, and sol-gel which fits into the broader spectrum of a dry technique. Historical data indicate that there are techniques such as electroplating may have been used for at least 2,000 years. While significant developments have been made in these technologies over the past few decades. These developments have been mainly targeted at improving the efficiency of deposition (often through minimization of waste by-products generation) increasing the quality of coatings (through optimization of the deposition parameters), and broadening the range of materials that may be deposited (by either surface modification techniques and/or the continuous development of new coating materials and deposition processes). Improvements in the context of metallic coatings may include a reduction in porosity, a densification of structure, a reduction in oxide and nitride content, resulting in enhanced corrosion protection of the coated material and thus an improvement in surface aesthetics. Other advantages are increased reflectivity and increased hardness.

Combined with along with the intrinsic stresses the present invention, in turn, can lead to coherent built up initial stress. The common point for all the current advances technique is applicable to considering 3D shape forming the substrate who can temperature pre50mation, as it most of the depositors relies on the to remove substrate of the heat or any product, at least during a protection. Moreover all of the metal directional deposition previous methods ozone the substrate to fulfill some initial coating step.

IX.4.1. Electroplating

Electroplating is a method for applying metallic coatings that requires electrochemical dissolution of a metal as ions in a liquid and an application of an electrical current to plate the ions onto the substrate. Baths generally contain the dissolved metallic salts of interest and other chemicals to help with the process. Components of the bath consumed in the process need to be periodically replaced. Composition of the metals deposited, amperage, temperature and pH of the bath, current density, and type and placement of electrodes can all affect the final product. The use of jigs allows for returned electrical currents to follow predictable paths, ensuring an even distribution of deposited metals. Too low of a current can cause pitting or rough coatings and too high of a current can cause an uneven coating. There are also external threats to the process such as machining, buffing, and either deliberate or accidental contamination. One considerable virtue of electroplated finishes is that they result in coatings that have remarkably uniform thicknesses and can be controlled within relatively narrow limits. Therefore, they are used frequently to provide finishes possessing a high degree of brilliance, and lend themselves readily to the use of various types of mechanical or chemical treatments in order to obtain special effects such as etching, frost, satin, brushed, or other textured finishes. Furthermore, excellent adhesion qualities including: (a) metal tightly adhered to the substrate; and (b) high ductility of the metal, are further realized because the plating is actually a physiological growth of the metal onto the substrate. This procedure is primarily utilized in the fabrication of electronic printed wire boards, where the coating serves both as an adherence promoter for the transferred image and also as a resistant material, the coating being removed in those places where the geometric pattern of the circuit board image is not desired. The coating is also used to cover automobile and truck bumpers, grilles, and hubcaps, where it is desired to have an attractive, shiny part that has resistance to such factors as road salts, exhaust gases, and the weather

IX.4.2. Thermal spraying

Metals and other materials can be deposited onto surfaces using a technique known as thermal spraying. A wide variety of materials in a range of forms can be used as a feedstock, with the deposition typically taking place at high temperatures. Thermal spraying is a prolific and versatile technique with multiple variants available, such as flame spraying and plasma spraying. The coatings can be applied to very different kinds of substrates and can have thicknesses from a few microns to a few millimeters. Large areas can be efficiently coated, which can be difficult using alternative methods. The coatings generated by thermal spraying are used in conjunction to certain applications, in which high importance is given to wear and heat resistance [6].

Due to their texture, sprayed coatings typically are thicker than other industrial coatings. Since their integrity closely depends on the mechanical bonding to the substrate, extensive surface preparation is mandatory, which is a downside to the method. In spite of being a very old technology, thermal spraying is still an interesting and promising deposition technique. In the present day, besides simple coatings for convenience, advanced coatings are available to provide new functions and capabilities. Some of the most straightforward functional coatings are thermal barriers coatings for advanced turbines and protective or functional coatings on the aerospace and energy applications [3]. The potential benefits thermal sprayed coatings can provide in such fields are vast. Nevertheless, adhesion still remains one of the most critical features to ensure full performance of these coatings. With an increasing effort to improve the operational efficiency of existing and future plants, thermal barriers coatings are being used to protect key components of the most stressed parts of the turbines in advanced combined cycle plants or aviation components. Spray coatings are often used on automotive and defense specific applications to avoid fretting wear problems. On the naval defense systems, different types of claddings, mostly flame sprayed are being used to avoid the corrosion on the structures. Several issues such as thermal mismatch stresses generated by the differential thermal expansion, surface preparation and particulate adhesion are analyzed in the present work. Efforts made in these areas aiming to enhance the adhesion of these coatings are reviewed in the final sections.

IX.5. Applications of metallic coatings

Metallic coatings are used in a large number of industries, and provide a wide range of product improvement opportunities [2]. Through the application of an appropriate coating type—thickness, and method, manufacturers are often able to improve the aesthetic, functional, and/or longevity performance of otherwise less-durable or inferior products. These improvements are typically cost-effective due to the extremely thin nature of the coatings and their ability to be applied with high throughputs. Other methods of part improvement such as heat treating, welding, bulk materials with custom properties, or usage of high-performance plastics are often lower throughputs and require large capital equipment that distracts from innovation and product differentiation. Investment in an appropriate coating, however, can be very effective in boosting the performance and marketing of a product. The most common industry sectors which employ coatings and use them to create highly specialized products are the automotive and aerospace industries. These industries have many unique needs and in automotive, for example, body coatings are necessary to provide both protection against corrosion and to ensure durability, appearance, and a cost that is acceptable to the consumer. Aerospace coatings are far more specialized, with applications ranging from high-temperature control coatings that exhibit a low thermal conductivity to polymeric coatings that facilitate lightning strikes. The automotive model will be used in this paper as a means of understanding in greater detail the coating methods used in industry as well as the instruments and standards needed to maintain such levels of quality. There is an attempt to predict where the industry trends for coating automotive bodies are heading, and how this will affect the consumer in terms of cost and durability. Other more detailed systems or infrastructural strategies will be considered in the hopes that those interested in entering the field of automotive coatings will find a valuable entrance point. Some other, more light, hearted and consumer-oriented applications of coatings that will be discussed are the use of coatings in unique consumer products and electronics. This may perhaps serve as a means of providing a greater understanding to the general public of the role that coatings play in their everyday lives. The process will be outlined, and particular coatings that exhibit special properties that effectively or undetectably change some manner of consumer goods will be discussed. Additionally, the use of these coatings will be analyzed in regards to environmental sustainability. This will be made clear through the examination of infrastructural needs that industries supplying coatings to these sectors should attempt to guarantee, as well as practices and standards both in selection and application that manufacturers should seek to maintain.

IX.5.1. Automotive industry

The importance for metallic coatings has grown in the rapid growing world-wide industries. They play not only a functional task in increasing the durability of components, but also are aesthetically appealing. Among the numerous coatings obtainable, metallic coatings are amongst the most utilized because many fundamentals find it optimal to plate with nickel, chromium or zinc alloys. The exceptional physical properties and historic associations of metals have made them the materials of option for automotive components throughout the existence of the motor vehicle [2]. Although comparative hefty technological strides have been experienced in the design of vehicles, the method in which they are constructed, and the manufacturing systems employed, the materials thereof have essentially remained the same.

Vehicles are subject to the harshest of environments, with components having to withstand maintenance standstills such as engine heat, stone abrasions, seesawing loads on suspension components, impacts, and harsh weather surroundings. Primarily threatened by such environments utilized in the automotive industries are vehicle engines, their trims, and body panels such as engine heads, wheels, valve trims, engine nozzles, engine crankshafts, engine bolts, nuts and washers, vehicle door and window trim strips, vehicle bumpers, decorative vehicle body panels and surrounding mouldings, air inlets and vehicle exhaust/ inlet trims.

Vehicle engines, for instance, are generally fabricated of alloy and coated with a nickel layer using an electro-less technique in which the engine parts are submerged in nickel bath, and assembled afterwards. The engine parts then require to sustain environmental temperature changes, and thus the nickel layer is required for heat resistance. Recent projects from universities have driven to the commencement of particular laser technologies. These technologies enable the cost efficient plating of engine parts without using a wet chemical technique. Successful findings from such automation turning trials include components with one singular profile such as engine cranks and engine bolts, nuts and washers utilized in conjunction with advanced anti-vibration systems to cater for load pressure. Additional advantageous features from such findings include an appreciable drop in maintenance costs of the particular components, and thus have a substantial market probability.

IX.5.2. Aerospace industry

Skipping the regathering of parts from the current line, the mix of forward scattered and elastically spread particles entering the initial collector may be such that the probability of randomly directed particles reaching the collector while actively illuminated by a laser is high. Versatile yet robust sample container alignment affords a real-time in-process exhaust pollution monitoring system. Measurements of exhaust gases often require that samples with particulate matter (PM) be presented to a gas analyzer, most conveniently a laser spectrometer. Potentially, samples may be collected any phase at a point where the latter possesses an appreciable pulsed component and the phases must be aligned such that particles are presented to an axisymmetric illumination volume. Subsequently processed to extract gaseous PM at an inflow of the laser beam produces regions of optical shadow. Emerging in-process exhaust pollution monitoring systems require a versatile yet robust sample container that is readily deployable on a wide range of vehicle makes and models. To meet this requirement a container has been developed that readily supplies samples to an approved standardized electronic exhaust emission testing system. A video-based alignment vision system facilitates reliable real-time alignment to achieve the necessary particle presentation and laser beam intersection. Ensuring robust container alignment despite potential analysis-line resonances [1].

- **Innovations in Metallic Coatings**

Innovations in cladding, coating, and plating are at the forefront of material science developments. Breakthroughs in this field define shaping and pushing the limits within traditional as well as innovative applications. It is at the top of the innovations enriching possibilities of coating adhesion to the substrate as well as enhancing properties improving wear and corrosion resistance, hardness, ability to isolate from external influence, offering materials with low friction and self-healing features as well as ability to create conducting or anti-static films on non-conductors. Continuous research, as well as the development of the field, provides the possibility of obtaining conductive paint from anticorrosion . Moreover, coatings could be improved by giving long-term protection to the human body, which could be faced by medical equipment or implants. Special attention is given to an attack cladding method by the metal foam powder, as one of the most advanced materials and techniques giving new possibilities in terms of coatings.

These new materials of the "third generation" are in the form of a lightweight porous metallic interconnected network, consisting mainly of surface areas, which leads to a large relative surface compared to a small amount of mass. Therefore, the inter-diffusion of the coating and substrate is significantly improved. Metal foams are also extreme conductors of heat, as well as electricity. In its powder form, on the other hand, it can be easily deposited on the substrate, which, blended with a variety of metals as well polymers, gives an infinite number of compositions. It is developed and patented a revolutionary technology to produce metal foam sealed coatings using metal foam powders and cladding from the thermoset rod, so to create a varnish or enamel-like coating leading to the most significant results. The patent version of coating techniques uses a simple to apply methodology based on spraying metal foam onto the degreased and pre-heated surface of the substrate, so it obtains cladding from a thermoset rod, and then post reactively cured in flexible conditions, depending on the rod composition for a short duration. The process is also particularly eco-friendly, as it is energy efficient simply and in a small amount of time most of the vapors of the cladding rod are evaporated, so the rod obtains the high-filled particles with no or minimal emissions of hazardous organic substances, what is required to lubricant-based addictive.

Nanotechnology in Metallic Coatings

Nanotechnology represents an innovative approach in the field of metallic coatings. Nanoscale materials may entirely transform classical coatings due to size effects and the peculiar properties of nanocrystalline materials. The historical and conceptual background of nanoscience and nanotechnology is described, focusing on the physical and chemical processes that determine the properties of materials. Attention is drawn on the relationship between the dimension of the structures and the properties of the matter as well as the difference between bulk and nanosize materials is treated. Different nanostructured coatings, their kind of bonding and growth, and the methods used to analyze them are described. A basic statistic and a review of several simple nanostructured growth models, focused especially on the interactions between coatings and their surfaces, are presented [7].

Metallic structures with at least one dimension in the nanometer range may exhibit quite new and peculiar properties, which usually differ from those of the bulk materials from which they come. Performance of many kinds of products could be substantially improved by introducing the possibility of coatings consisting of plates or reinforcements with dimensions at the nanometer scale. Benefits that could be obtained are higher stiffness, strength, tenacity, and resistance to thermal, chemical and mechanical wear. An overview of interesting literature on nanocoatings applied to amorphous polymers is given. Special attention is focused on barrier properties of these coatings and their possible applications in the packaging industry, considering recent progresses on biodegradable and edible polymers. Research is ongoing to explore the capabilities of different excellent physical and chemical deposition techniques for the growth of nanostructured films on suitably primed polymer surfaces and the performance of these new systems is being tested by means of morphological and functional analysis. Focus is on more than forty patents on plasma deposition of nanocoatings applied to polymeric substrates, in order to ascertain the state of the research in this field, especially looking at materials and markets of readily commercially available products. Emerging technologies able to substitute PECVD for increasing productivity and marketability are also explored, such as PE-CVD and Plasma Impulse Chemical Vapor Deposition.

Future Trends and Developments in Metallic Coatings

Metallic coatings account for a substantial share of the protective coatings' segment across a broad array of industries. They are widely used and can be formulated with several metallic elements or various forms, including pure metals, alloys, and more complex types, such as cermets or metal-matrix composites. The formulators can also enhance their performance through multiple strategies during deposition or by incorporating other elements into the coating microstructure. Metallic coatings are remarkably versatile and can range from precious metal jewelry to the cutting-edge tools and equipment required in the most demanding industries. Industries, such as aerospace or the automotive sector, are in constant evolution, and the metallic coatings they demand are not an exception to this rule. Therefore, market demand shifts and technological progress generate a continuous evolution in the field of metal coatings, as new materials are required to fit the ever-increasing number of applications.

Regarding metallic coatings, a process rooted in the fabrication of jewelry has quickly evolved to the high-tech microelectronics found within computers and other electronics. Common examples include aerospace coatings, radiation shielding against UV radiation, and wear-and-galling protection on cutting tools. Additional complexities in the coating process have been found to provide additional functionality of the coating. Regarding the environmental impact, metallic coatings have been developed that are toxic free and are finding wide application in consumer goods and the surgical industry. Functionalities are emerging as the use of metallic coatings continues to expand across multiple industries. This topic is correlated with a growing industrial demand for smarter coatings that can either trigger a color change in the presence of some biocompatibility coating or exhibit a decreasing coefficient of friction. A series of coatings are being formulated to meet some particular requirements and are proving beneficial to a rising number of applications.

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CHAPTER X

CORROSION MONITORING TECHNIQUES AND APPLICATIONS

Chapter X : Corrosion monitoring techniques and applications

X.1. Introduction to corrosion conitoring

Corrosion monitoring is an essential part of any corrosion management program. Such deficiencies prevent the ability to know what is happening to steel reinforcement in concrete structures where the embedded steel is an electrical conductor. Corrosion monitoring is carried out using a set of detectors, data storage and transmission systems. The implemented system analyzes the detected data and assesses the corrosion state of the structure and its components. However, the detector is a crucial component in a monitoring system, as it determines the overall reliability of the system corrosion information. Among different types of detectors, metal coupons are one of the most widely used and reliable methods for corrosion detection in different industries. It can be used in oil and gas production, refined petroleum plants, industrial water treatment, shipping conditions, etc. In the metal coupon method, the metal coupon is exposed to corrosive conditions to calculate the mean corrosion rate from the mass loss, mass gain, or coulometric decrease of corrosion products. Despite their apparent reliability, there have been numerous issues such as leaks, moisture penetration, labor costs, vandalism, etc. These shortcomings prevent effective corrosion monitoring and risk management in many structures' reaction suddenly, completely and unexpectedly. It is also costly to ramp up and properly carry out a curve fit.

This technique does not provide real-time measurements, and corrosion monitoring usually relies on electronic corrosion sensors or probes. A huge variety of such electronic systems have been and continue to be offered around the world. These electronic corrosion sensors or probes continuously or semi-continuously transmit corrosion information to the system. Regardless of design, each corrosion probe needs to verify long-term reliability under real structural processing and/or environmental conditions before actual commissioning. The proper corrosion management algorithm in the data acquisition system provides performance data and a basis for life prediction of the under-study system. Therefore, continued development of these electronic devices has a high level of importance, as corrosion monitoring is essential in corrosion prevention and control. The reliability and robustness of the electronic monitoring devices, including both the sensor component(s) and other associated parts, are critical issues. Considerable research needs to be conducted to check the reliability and working principles of electrode-based detectors, especially 3D structured ones, which are still under development.

X.2. Corrosion monitoring techniques

Corrosion, the natural degradation of metals is one of the most critical problems in the industry as it greatly increases production costs (Komary et al., 2023). Corrosion monitoring can be carried out by three principal means; detection of the corrosion, data storage in a database, and data transmission to the monitoring system. There are numerous low-cost corrosion detection methods used in industry depending on the intended monitoring environment. Metal coupons are one of the most routine used, simplest, oldest, cost-effective, and well-known corrosion detection methods in many industries and laboratory tests. However, this technique does not provide real-time or near real-time measurements.

Corrosion monitoring normally relies on electronic corrosion sensors or probes that can detect corrosion and transmit the corrosion information to the system. The continued development of these electronic devices is crucial as corrosion monitoring needs to be performed as a preventive and control measurement against corrosion. Corrosion monitoring is usually known as a multidisciplinary task, and as it is mentioned above, often two or more methods are needed to manage corrosion monitoring needs. There is a variety of corrosion monitoring techniques, procedures, and monitoring devices; however, all corrosion monitoring techniques can be categorized into physical techniques and electrochemical techniques. The electrochemical detection and monitoring procedures are much more efficient compared with physical methods. Electrochemical techniques can be distinguished by their broad accessibility, low cost, portability, efficiency, sensitivity to low corrosion rates, and the short experimental period needed to achieve reliable results. However, the issue of monitoring for field applications is much more complex compared with laboratory experiments and the methods must be dependable, straightforward, and repeatable for long-term corrosion monitoring.

X.2.1. Electrochemical methods

Corrosion processes can be efficiently monitored through low-cost electrochemical methods. An overview of the theory, suitable measurement systems, and application examples for one of these electrochemical techniques, called electrochemical noise (EN), is provided (Komary et al., 2023). Corrosion poses a significant challenge associated with costs and environmental safety. Continuous and expanding efforts are dedicated to monitoring processes that lead to possible corrosion damage. When designing and implementing corrosion monitoring strategies, engineers have to solve many problems while fulfilling requirements from operators and decision-makers. To develop suitable electrochemical monitoring systems, an overview of the theory, measurement systems, and practical setups of one of the electrochemical methods, called electrochemical noises, is given.

Electrochemical Noise is a promising and low-cost approach compared to more sophisticated laser-based and industrial use systems. The FC probe is an example of a practical implementation of EN measurements providing insight into soil corrosion processes. Many commercial pH, conductivity, and potential data loggers are currently in use. To analyze proper sensing methods, relevant types of corrosion during pipeline operation, and their indications in the urban environment, commonly used monitoring systems are briefly reviewed. Furthermore, low-cost alternatives to the industrial systems currently in use are proposed in this study. For application in a Mexican city, a simple PCB-designed potentiostat was built to measure electrochemical parameters such as potential and current, giving insight into various corrosion processes. Suitable analog and digital electronic components were investigated to design alternative stations for measuring pH, noise, and conductivity at a low cost.

Buy- or home-made amperometric, potentiometric, and conductive-dominating measuring cells/stations achieving specific measurement tasks in monitoring systems were also presented. The buyable or recommended electronic components are listed in detail. Ternary diagrams were applied to select satisfactory possible arrangements of cheap handheld potentiostats needed for noise measurements to monitor possible hazardous corrosion processes like pitting in various pipelines. Future plans to improve software were also described. Furthermore, the use of EN to investigate pit growth on CuNi alloys, stress corrosion crack behaviors of API X80 pipelines, copper corrosion in soil pipes, and microbial corrosion of alloy C276 under unconventional measurements are also reviewed.

X.2.2. Ultrasonic testing

Ultrasonic testing (UT) is one of the most commonly used non-intrusive inspection techniques in the industry due to its versatility, safety, and effectiveness. UT is based on sending pulsed ultrasonic signals into the monitored component and capturing the reflected signals from the internal and/or external boundaries. The time of flight of the reflections provides information about the thickness, while the shape and amplitude of the returned signals contain information about flaws and damaging mechanisms. A number of successive UT testing can be performed on the same component to monitor the progression of defects and/or damage (Wasif et al., 2023). The time of flight of the signals can change due to changes in the propagation velocity, which in turn depends on the density and/or elasticity. Number and/or types of reflections can change due to delamination, cracking, and various other phenomena. Signals can attenuate and distort for various reasons, such as changes in the interface roughness, scatterers, and/or internal material structure. All of these effects can be of different character and can have different impacts depending on the damage mechanism, component geometry, and monitoring setup.

The ultrasonic time of flight techniques have been used in a number of works for quantifying corrosion wall thinning. In all cases, the time of flight is measured using a single signal, and the thickness monitoring is limited to just that single location. A number of techniques have been proposed to monitor the time-of-flight differences due to wall refraction (Raišutis et al., 2023). A number of guided wave based techniques have also been proposed that deal with the earlier mentioned challenges faced by this technique, but the resulting system is still intrusive and complex to install and require periodic maintenance.

In addition to detecting ECT, there are also a number of works that cover the quantification of the corrosion damage. Taken the application of clean steam generation as an example, in order to logically and rationally qualify the electrochemical corrosive hydrogen damage in the 304 stainless steel pipes of the wet area of this system, GIT was combined with theoretical analysis based on the Tada solution to establish a qualitative and quantitative method one of the important issues is to find an appropriate propagation mechanism. Various techniques are covered, including purely airborne emission acoustic emission, intrusive EMAT ultrasonic guided waves (UGW), and non-intrusive contact normal direction UGW transducers.

X.2.3. Visual inspection

Visual inspection is one of the most often utilized yet most crucial techniques for corrosion monitoring. It can be performed by trained staff and requires only straightforward equipment for the operator. Since corrosion products can also be viewed in the visible spectrum, visual inspection can be performed from either the top or the side. Video and photographic data from visual inspection can serve as inspectors' notes and reports, which are essential for the subsequent appropriate maintenance work (Wasif et al., 2023).

Visual inspections necessitate some prior knowledge of the detected components, major-impact areas, and experience in interpreting the pictures. Entangled photo data will provide little value (Latif et al., 2020). Using thorough knowledge of surfaces and items, codification aids in standardizing terminology and views for operator-to-operator and operator-to-year consistency. This is achievable with relatively uncomplicated and functional techniques since visual data sets are small and need little processing, while the incident aspects that influence corrosion finish throughout its occurrence are hard to describe quantitatively. The processing time is negligible in comparison to the operator observation, and post-event comments of corrosion are still possible.

The coded photo documentation captures copies of initial surfaces before maintenance action. Moreover, lengthy series of images may lead to pattern acknowledgment and association of an initiation, so that corrosion occurrence—hours after the surface was fresh—may label abnormal surfaces. Today's automated corrosion monitoring and inspection systems rely on gathering and processing a great deal of data. Pattern recognition for comparing and associating items is a difficult subject that is still incomplete.

X.2.3.1. Weight loss measurement

The weight loss measurement method involves the use of a metal coupon. The coupon is allowed to corrode for a period of time with earlier weight recorded as W1. After the time period, the weight of the coupon is again measured as W2. The weight loss can then be calculated as follows W = W1 – W2 (Wasif et al., 2023). This method falls under the category of intrusive techniques since the coupon needs to be cut and weight needs to be measured. This method can also be used in combination with other techniques. Use of the method can be made continuously without taking measurement of weight and could be utilized especially in the analysis of quality of water in drinking water network. In this method, a metal coupon is put in a chamber with controlled conditions. Water to be analyzed is passed through this chamber. The coupon material, size of the chamber, inlet/outlet conditions of chamber are fixed. As the water is passed through this chamber, it comes in contact with the coupon generating corrosion at the interface. As long as the initial weight of the coupon is known, the coupon can be periodically removed and weighed to monitor corrosion without the need of keeping track of the water flow. If required, the coupon can also be cleaned and re-used. Corrosion rate monitoring and prediction is achieved by weight-loss measurement. The mechanical system where the coupon is to be mounted is analysed to develop design considerations. The simple mechanical sensor aims to be suitable for both existing and new systems. Maintenance actions are suggested to ensure long-term effectiveness of the sensor weight-loss coupon machining process.

X.2.4. Corrosion probes

Corrosion is one of the asset owners' main concerns, especially in the energy and power sector. Although huge costs are dedicated to the inspection and maintenance of corrosion in industry, corrosion accounts for 42 % of failures in structures. Costs to replace or repair these structures can be enormous, equivalent to 3-5% of the country's gross domestic product. A common type of corrosion scour of assets in energy and power is the loss of wall thickness in the pipelines due to erosion or pitting or general corrosion. This can lead to leaking and ruptures, catastrophic explosions, and deaths if not detected and mitigated in time (Wasif et al., 2023). Detection of corrosion at an early stage and continuous monitoring is imperative to avoid these failures. Monitoring in this context refers to the continuous data acquisition on the state of the component. The work presented in this thesis is directed toward corrosion monitoring and has a strong application in high loop heat pipes. These pipes are typically made of copper and are prone to pitting corrosion, specifically when subjected to high temperature and aggressive working fluids.

A number of corrosion monitoring techniques are employed in the industry. These can be divided into two categories: Intrusive and Non-intrusive. Intrusive techniques involve measurement of corrosion rate by exposing the coupons or probes to the flow conditions. In principal, these devices are permanently installed on the pipe wall and provide the average corrosion rate of the entire area exposed to the fluid as average weight losses over known areas periodically retrieved and weighed (Zajec et al., 2018). There are three main types of intrusive techniques: Loss of mass, Voltage drop, and Estimation of corrosion potential. Non-intrusive methods are installed on the component for continued corrosion monitoring with no direct exposure to the corrosive flow. They entail induction corrosion monitoring, electrical resistance measurement (ER), pressure wave or guided wave, ultrasonic velocity profiling (UVP), and model-based corrosion monitoring. Applied to pipes undergoing uniform wall loss, guided wave transducers can screen large pipe lengths and cover 360° of the pipe circumference. However, tests conducted on the stability of the permanently installed guided wave sensors in high loop heat pipes have revealed that the signals are highly affected by variation in temperature. The second most commonly used corrosion monitoring device is the ultrasonic thickness (UT) gauge.

X.3. Advanced monitoring technologies

Corrosion is a major concern for asset owners in the energy and power sectors, including oil and gas, petrochemicals and chemicals, utilities, and power generation. This includes corrosion, which plays a governing role in 30%-50% of failure of such equipment. Marine environments account for around 40% of corrosion, which incurs a loss of over 200 billion dollars to the US economy. Detection of corrosion at an early stage and continuous monitoring are therefore imperative to avoid these failures. Corrosion monitoring involves continuous data acquisition on the state of the component. A number of corrosion monitoring techniques i.e., non-intrusive or intrusive monitoring techniques, are employed in the industry. These can be broadly divided into two categories: Intrusive and Non-intrusive techniques, i.e., intrusive and non-intrusive methods. Intrusive techniques which are involved in measurement of corrosion rate by exposing the coupons or probes to the flow conditions. Non-intrusive methods such as ultrasonic, guided waves, surface acoustic waves, optical fibers, and capacitance measurement. These methods are non-intrusive in nature since these methods are permanently installed on the component for corrosion monitoring. Guided wave transducers can screen large pipe lengths and cover 360° of the pipe circumference. However, tests conducted on the stability of the permanently installed guided wave sensors have revealed that the signals are highly affected by the variation in temperature. Ultrasonic thickness (UT) gauge is by far the most commonly used corrosion monitoring device (Wasif et al., 2023).

Corrosion monitoring is carried out using a set of detectors, data storage and transmission systems. Among different types of detectors, metal coupons are one of the most widely used and reliable methods for corrosion detection in different industries. Metal coupons are made out of the same base metal as that of the part in the asset that is to be monitored and are exposed to corrosive conditions, usually using specialized scientists that allow for the calculation of the mean corrosion rate. However, this technique overall does not provide real-time measurements, and monitoring usually relies on electronic corrosion sensors or probes. These electronic corrosion sensors continuously transmit corrosion information to the system (Komary et al., 2023). Therefore, the continued development of these electronic devices has a high level of importance as corrosion monitoring is essential in the broad field of corrosion prevention and control.

X.3.1. Smart coatings

Smart coatings using passive IMs were developed to allow measurement of the degradation of protective coatings on modern steel structures. To experimentally verify the feasibility of the proposed coating degradation monitoring approach, a laboratory-scale experiment was made using coatings with different EIS characteristics, emulating the effects of different degradation levels. The smart coating was fabricated using a wire helix IM coated by specific smart coating materials, including dielectric and conductive polymer blends, and tested over a frequency range of 1 Hz to 1 MHz at room temperature. To map through-site impedance changes, a multi-frequency analysis approach was employed. The assessment of experimental results showed that the smart coatings exhibited progressively shifted multi-parametric shifts as the coating degradation increased, which agree well with the corresponding mechanical damages captured by the naked eye and observed using SEM images.

Modern steel structures often suffer long time exposure to aggressive service environments, and their structural reliability is dependent on the integrity of protective coatings, which are fundamental components in corrosion management. This research proposed the development of smart coatings using passive IMs that can directly measure the degradation of protective coatings on modern steel structures rather than indirectly assessing the integrity of protective coatings of steel structures through the degradation of underlying components, as widely adopted in practice. The fundamental concept and prototype of smart coatings was presented and the feasibility of the proposed coating degradation monitoring approach was experimentally verified.

Compared with many other infrastructures, modern steel structures are often fully coated, and the coating integrity is critical to the overall structural integrity as it is the first defence line against corrosion. Existing methods for monitoring the integrity of protective coatings on steel structures, most of which are indirect, are limited in terms of a full access to concern regions, long-distance monitoring, reliability during harsh conditions, and the impact on the normal service of structures. Therefore, a smart coating using passive IMs is developed to allow a direct and on-line access of the coating degradation monitoring. The smart coating consists of i) a wire helix IM designed to allow through-coating impedance measurement at one end of the coated structure without impacting the service of structures, ii) dielectric polymer and conductive polymer blend smart coating materials that can be applied to different design- and construction-involved steel structures.

X.3.2. Wireless sensor networks

In the past decade, more applications of wireless technology in corrosion monitoring have been reported. Wireless sensor networks (WSN) connect independent sensor nodes to a monitoring center and provide a cost-efficient solution for monitoring corrosion of large infrastructure systems on a daily basis. In a WSN, remote micro-sensor nodes are powered by a small battery, which may need replacement every couple of years depending on the monitoring frequency. In recent years, energy harvesting techniques, which convert ambient energy into electricity, with WSN have been explored as a promising way to sustain long-lived WSN smart structures with little maintenance (Qiao et al., 2014).

Compared with wired sensor networks, WSN is more flexible, cost-effective, and less invasive. A WSN consists of a number of independent micro-sensor nodes, which can automatically connect to a central monitoring station to transmit the monitored data. Each micro-sensor node includes sensors, a microcontroller, a wireless radio transceiver, and a power supply, and is able to detect, process, and transmit data wirelessly to a ground station. A monitoring station processes the collected data and transmits the results to end users. Because of the cost-effective design of micro-sensor nodes, a network of thousands of sensing nodes can be implemented to monitor a large structure (Komary et al., 2023). In addition to low-cost, WSN-enabled smart structures are also less invasive because of power wires and data cables. Finally, scaling up the number of nodes and installing new sensors is easier in WSN, as it may just require small sensors without power wires. Because of this flexibility and low cost, WSN technology has been widely adopted in various applications including structural health monitoring.

Unlike embedded sensors usually applied in wired networks, nodes in WSN are wireless micro-devices powered by batteries or energy harvesting units. The wireless mechanism enables the sensors to be easily deployed at hard-to-access locations, while the limitation of battery life is a typical problem. Depending on the monitoring frequency, the sensor node could need maintenance and battery replacement every couple of years. In order to sustain long-lived WSNs with little maintenance, a number of energy harvesting techniques have been studied such as vibration, thermal, solar, and RF energy harvesting.

X.3.3. Remote sensing techniques

Corrosion is a physical phenomenon that occurs universally and uncontrollably on metals through electrochemical reactions, which can pose severe economic risks to society. There are several techniques classified under monitoring methods of corrosion, out of which remote sensing techniques are discussed in this paper. To track the health of the pipelines in the oil industry, (Komary et al., 2023) developed a low-cost wireless passive ultrasound-based monitoring device with an anchor-free wireless transmission mechanism and an energy harvesting circuit that increases the efficiency of the battery-less monitoring device. introduced a low-cost wireless passive ultrasound-based monitoring device for steel pipelines with a similar ultrasonic measurement process but only focusing on temperature measurement to remove temperature effects. In 2021, proposed a remote ultrasound technique for corrosion monitoring in civil structures. The accuracy of the signals at different locations is used to indirectly inform the thickness measurements at those regions. proposed a remotely accessible framework for monitoring corrosion in aircraft using a laser airborne ultrasound transducer.

The effectiveness of ultrasound signals enables very frequent thickness measurements as compared to traditional techniques, with which uncertain noise-free corrosion history of steel rebar in concrete over many years are successfully reconstructed. Researchers have also introduced several corrosion monitoring devices based on Faradays law of electromagnetic induction (EMI) for the early assessment of corrosion in reinforced concrete (RC) structures.

Some of recent works focus on developing low-cost corrosion monitoring solutions for concrete structures. Authors obtained the EMI signal by passing a low-frequency AC current through a coil positioned around the rebar while the other coil is placed just above the concrete surface for monitoring the potential difference. Another self-powered low-cost continuous monitoring device of EMI sensors was developed with a focus on testing its functionality in a partially immersed coastal RC bridge.

Another approach by many researchers is to introduce novel sensing methods based on the magnetic field induced by the electrochemical activity from a uniform corrosion mechanism of a metal sample, including reinforced concrete structures, coated steel rebar, galvanizing, and ship hull application. Concerns about safety, high costs, and recent developments in image detection sensors, AI technology, etc., have highlighted the urge for the development of a low-cost, safe, and quantitative solution known as image recognition (IR) or image analysis technology. Experimentally, the phenomenon of corrosion leads to changes in the surface structure, morphology, and composition of the materials, which are the basis of image-related technology, by image sensors. By implementing image recognition technologies, they can obtain the type and extent of corrosion.

X.3.4. Machine learning applications

Acoustic emission technique can be used to monitor corrosion processes and predict severity levels by extracting specific features from different AE waves. Over the last decades, machine learning has garnered interest in analyzing signals acquired from various sensors and non-destructive tested specimens in civil engineering including corrosion monitoring. The supervised learning model was used to build machine learning-based prediction models for ranking the 1st risk factors of inclusive depression in participants. The progressive degradation of mechanical properties has been predicted using a multiple input neural network approach and classified into 4 different classes using the artificial neural networks method. Online network learning based on the multi-layered feedback-perceptron neural networks was used for the implementation of the supervised learning approach to detect damage in a composite water tank. To monitor the structural health of hard rock tunnel during blasting activities using long short-term memory recurrent neural networks identifies the normal and anomalous conditions of an array of fiber optic sensors.

Batch learning was used to develop a model of the pipe internal corrosion monitoring system. The corrosion prediction using a hybrid long short-term memory network with multi-head attention based on the monitored data of pipeline operation was provided. In a 3-dimensional pipeline structure, an inductive FEA technique based on multi-head attention multi-resolution LSTM network was applied to predict the structure fatigue life and detect corrosion. The fatigue life and fatigue failure locations prediction were developed using hybrid machine learning approaches in 2D and 3D pipeline structures based on monitoring data of pipe detectors. Spatial-temporal attention GNNs were recommended to analyze the corrosion of complex urban pipe networks.

Machine learning predictive models use acoustic emission (AE) technique for corrosion monitoring. Fatigue crack growth rates of aluminum alloy are predicted using a hybrid deep learning approach. Acoustic emission wireless sensor nodes detect temperature-induced surface crack growth based on a multi-channel deep learning network technique. The position and size of crack detection are categorized into four classes using deep learning convolutional network technique.

X.4. Factors affecting corrosion

Corrosion is the degradation of the mechanical properties of metals due to a gradual loss of metallic material due to electrochemical processes and interactions with the medium surrounding it. Corrosion processes involve multiple phases. A review of phenomena influencing corrosion mechanisms is presented, including the states of the material in space, the evolution of those phases in time as they interact with the environment, and macroscopic expressions. Monitoring corrosion is of paramount importance, and several methods exist to obtain information about corrosion state and evolvement (Komary et al., 2023). Several methods can measure corrosion, sometimes presenting new physical principles to detect potentially unreported corrosion mechanisms. The methods reviewed are grouped according to sensing physical principles, including electrochemical approaches, optical techniques, mass loss techniques, mechanical properties monitoring, humidity sensing, and other phenomena.

Corrosion is an ever-present danger for all metallic structures in a humid environment. Corrosion can lead to catastrophic events, loss of lives, and huge expenses for government authorities and industries. Assets are often remotely located, requiring extensive monitoring to frequently check for potential corrosion. This is energy-straining and costly, necessitating alternative monitoring techniques to prevent avoidable incidents. Smart materials with the capability to detect and report corrosion are highly sought after. There are several alternatives to traditional monitoring techniques, but they are often either too complex to manufacture or too expensive to consider. To have a high impact on a global level, ideally, the designed smart materials should be low-cost, universal, and easy to manufacture setups adaptable to strict industrial environments.

Corrosion is one of the principal causes for metal integrity losses, leading to malfunctions (accidents) and, in the worst case, catastrophic failures in load-bearing structures, buildings, bridges, pipelines, military assets, offshore constructions, etc. These costs are so high worldwide that they can never be estimated accurately; it is thought to cost 3-5% of the gross domestic product in developed countries and even more in developing nations. Corrosion forms immediately after a metallic component is immersed and exposed to the medium, immediately followed by the rate of its influence. In any environment, corrosion occurrence and its influence extent depend on several factors: oxide layer composition, coverage and formation, surface state (roughness, cracks, etc.), environmental composition (including pH, conductivity, temperature, salinity), total and local moisture content, gaseous agents, other atmospheric characteristics (for instance, UV), and several additional local factors.

X.5. Environmental conditions

In industries, where the presence of moisture is high, the enormous cost of inspection and maintenance induced by corrosion of pipelines represent the necessity of corrosion monitoring and inspection. However, there are huge costs associated with field rounds, including labor hours devoted for travelling to remote locations and removal and re-installation of corrosion probes. As a result, submerged and buried components such as long pipelines have not been monitored effectively yet, and the most economical approach is to apply monitoring techniques which can be employed at the surface of those pipelines (Wasif et al., 2023). Various non-intrusive techniques have been developed, but many of them can only detect early and small-scale corrosion and are not capable of detecting buried and internal corrosion defects, which are usually the main threat for long pipelines. This paper provides an overview of the state of art of several corrosion monitoring techniques developed in the last decade which are able to achieve the complicated goal of corrosion monitoring for buried long pipelines, including the magnetic induction based technique developed for buried conducting pipeline, the millimeter wave and microwave imaging based technique for buried and atmospheric pipeline, the microwave draw-wire type sensor for under-water structures (Yang et al., 2019).

Corrosion can occur anywhere and on any material that is exposed to conditions that are favorable to electrochemical oxidation. This includes on metals as well as on concrete, plastics, textiles such as cotton, etc. Corrosion is a major concern in many industries. It is estimated that its cost in the US is $442 billion per year. This cost is roughly equivalent to 3.1% of the US gross national product (GNP). In many industries, corrosion is the leading cause of failure. Various types of techniques are employed in the industry to monitor corrosion and include acoustic, capacitive, and electromagnetic wave based.

Batteries and galvanic cells are a priority for the detection and measurement of corrosive conditions in oil and gas production plants, wastewater and sewerage plants, and in environmental and atmospheric monitoring instruments. Sensors that measure corrosion data indirectly, by measuring the indicators of corrosion might be less sensitive than direct measurements, as they measure the cause rather than the effect. However, it is often important to be able to identify the exact location and/or type of corrosion to take appropriate measures for its mitigation and repair.

X.5.1. Material properties

Corrosion is an electrochemical reaction of a metal; whereby metal ions are removed from the metal surface. This occurs due to the tendency of metals to return to a more stable lower-energy state in the form of chemical compounds (oxides, hydroxides, salts, etc.). Therefore, metals must be protected so that they can continue to be useful in terms of their properties (Zajec et al., 2018). Corrosion is a common problem, which can occur everywhere, on land, underground, or underwater, but it especially causes problems with transport, chemical, and power plants, industrial and other buildings, bridges, tunnels, and pipelines. Due to corrosion, infrastructure and production plants can be damaged and their functionality hindered. These downtimes can be financially demanding, not only for big companies but also for small and middle-sized companies. It is estimated that the cost of corrosion incurred due to corrosion in the USA alone amounts to 276 billion dollars. In Europe, it corresponds to 547 billion euros (roughly, 1.5

billion euros per day) (Wasif et al., 2023). At the same time, corrosion represents a global challenge to human health, safety, and welfare and a major threat to energy security and sustainable development.

Corrosion monitoring is a crucial functionality of assessing the integrity state of structures, pipelines, tanks, and offshore installations. The goal is to detect dangerous corrosion defects at an early age and provide an effective way to reliably monitor and predict new defects as they develop. Due to the amount of money spent on and the damage caused by corrosion monitoring is an interesting field which is continually developed. Corrosion monitoring can be divided into intrusive and non-intrusive techniques. Intrusive (on-line) techniques involve measuring the corrosion rate of a component by exposing corrosion coupons or probes with known surface qualities (geometric profile, coating type, roughness, and alloy composition). Intrusive measurements are primarily used for condition assessment and monitoring of the integrity state of pipelines, tanks, and vessels, and can be found extensively in hydrocarbon processing, chemical, and desalination industries. There is a wide variety of technologies available for this purpose, and the most commonly used ones include: electrical resistance (ER), linear polarisation resistance (LPR), and weight loss measurements.

X.5.2. Protective coatings

An important aspect regarding the sustainability of steel structures is to ensure the structure is protected from corrosion. A number of surface coatings are available that play an important role in protecting these structures. An important part of the management of these structures is reliable and regular inspection along with methods for early detection of corrosion processes. In this paper, a development and application of sensors for monitoring the steel coating degradation and corrosion damage to steel substrate are presented. An encapsulated corrosion kit with integrated EIS sensors and ER probes was developed. To test its efficiency, steel probes were coated with selected coatings in the laboratory and their performance was assessed under various aggressive atmospheres, including salt, industrial and humid atmosphere. Corrosion rates increase as the temperature and humidity rise. The most problematic are areas with cyclic wetting and drying periods and areas prone to prolonged condensation. The presence of aggressive ions such as Cl^- and $SO4^{2-}$ also accelerate corrosion processes. Corrosion protection measures are applied, typically through the application of galvanic coatings and/or organic coatings using different types of paints. Such anticorrosion protection does not provide protection over the entire service life, but usually for a period of 15 to 20 years. After that time, protective coatings should be renewed. The rate of corrosion for protective coatings is in general predictable and well-understood (Zajec et al., 2018). The performance and availability of high priority structures can be greatly affected by corrosion damage. The application of protective coatings, frequent inspections and scheduled maintenance activities result in huge direct and indirect financial loss to organisations. The expeditious detection of coating failure and corrosion damage can result in precise and cost-effective condition-based maintenance. Coating failure and corrosion phenomena are driven by complex multi-disciplinary parameters. State-of-the-art prognostic models incorporate complex multi-disciplinary parameters, therefore a real-time prognostic monitoring system must acquire these complex parameters to allow accurate prediction. The work reported here covers the development of a real-time monitoring system using micro-sensors and includes the validation of the system through accelerated corrosion and coating failure testing. The system contains a remote terminal unit that includes a linear polarisation method for corrosion detection under the coating and a micro-strain gauge method for monitoring stress behaviour over the coating. The real-time monitoring system can be applied to remote, stationary and mobile assets to monitor the mechanical and chemical changes within coating-substrate systems (Latif et al., 2020).

X.6. Corrosion in different industries

Corrosion monitoring is carried out using a set of detectors, data storage, and transmission systems. Among different types of detectors, metal coupons are one of the most widely used and reliable methods used for corrosion detection in different industries. Metal coupons are exposed to corrosive conditions in order to calculate the mean corrosion rate. However, this technique does not provide real-time measurements, and usually, corrosion monitoring relies on electronic corrosion sensors or probes. These electronic corrosion sensors or probes continuously or semi-continuously transmit to the system corrosion information. Therefore, continued development of these electronic devices has a high level of importance as corrosion monitoring is one of the most essential components in corrosion prevention and control (Wasif et al., 2023).

Corrosion is a highly complex process involving, at least, two phases: the metal surface and the electrolyte. Therefore, corrosion monitoring is a multidisciplinary task, and very often, it is needed to observe two or more methods in order to adequately manage the monitoring needs. However, because almost all corrosion processes in nature take place in the aqueous phase, electrochemical detection and monitoring procedures are considered to be more efficient compared to physical methods (Komary et al., 2023). In addition, electrochemical techniques have several advantages, including sensitivity to low corrosion rates, a short experimental period, and a well-established theoretical understanding. Nevertheless, due to their high sensitivity and accuracy in corrosion measurements, monitoring for field applications is more complex than laboratory experiments. Electrochemical techniques that are appropriate for field applications should have two key properties. Although laboratory instrumentation of electrochemical measurements is usually complex, large, high-cost, and needs expert workforce training, appropriate instruments for field applications should be low-cost, compact, robust, and easy to use in order to maintain a simple way of handling data.

X.6.1. Oil and fas industry

Corrosion Monitoring Techniques and Applications

Oil and Gas Industry (O&G)

Corrosion can be simply defined as the deterioration of metal surfaces due to the interaction with a nearby environment (Aljarah et al., 2021). In the O & G industry, these metal surfaces are mainly the walls of the pipelines and storage tanks that transport, carry, and store oil and gas products. The corrosion environment in the O & G industry mainly consists of three main constituents: carbon dioxide (CO2), hydrogen sulfide (H2S), and water. Each type of corrosion that is related to one of these environments has a unique chemical reaction. When carbon dioxide (CO2) reacts with iron (Fe) and water, it produces iron carbonate (FeCO3) and hydrogen (H2). Iron sulfide (FeSx) is another corrosion product that is formed when hydrogen sulfide (H2S) reacts with iron (Fe). In the oil production process, oil is extracted from underground reservoirs using different mechanisms. Carbon dioxide (CO2) gas is normally injected into a reservoir to bring the oil to the surface and enhance the oil recovery. Large amounts of CO2 are injected into the reservoirs, which significantly enhances oil mobility. The CO2 gases mixing with water form carbonic acid (H2CO3), which reacts with iron, forming iron carbonate (FeCO3) and hydrogen (H2).

Hydrogen sulfide can react with the interior surfaces of the oil storage tanks and pipelines (iron) and form iron sulfide (FeSx). Corrosion of oil pipelines and storage tanks occurs in different forms, such as uniform or general metal loss, pitting corrosion, erosion–corrosion, stray current corrosion, and microbiologically influenced corrosion (MIC) (Oki et al., 2013). Uniform metal loss usually occurs along the internal and/or external surfaces of pipelines and storage tanks; it can be mitigated by using surface coating for the external surface and proper material selection for the internal surface. Pitting corrosion affects specific spots on the metal surface, usually occurring due to… The corrosion detection can be divided into two main categories: direct and indirect corrosion sensing.

X.6.2. Marine applications

Corrosion is a major concern for asset owners in the energy and power sectors. Enormous costs, which are oftentimes millions of US dollars, are made from inspection and maintenance of corrosion in the industry, particularly on oil and gas offshore platforms where corrosion-related accidents have been reported. Costs relate to inspection, maintenance, fines and litigation, facilities shutdown, lost production, and monitoring equipment (Wasif et al., 2023). Corrosion accounts for 42 percent of the number of failures, on the bases of both number of Failures in Structures and Cost related to Failures in Structures, corrosion is the leading cause of failures by a factor of 3.

Thickness loss is among the adverse effects of corrosion in pipes, equipment, and similar kinds of components. Detection of corrosion at early stages and continuous monitoring of corrosion is essential to avoid corrosion-related accidents. Monitoring involves continuous data acquisition on the state of the component, in real-time or near real-time. Monitoring data in turn is analyzed to assess the state of the component. A number of corrosion monitoring techniques are employed in the industry, broadly categorized as intrusive and non-intrusive. Intrusive techniques are those which involve inserting measurement devices within the pipe or inspecting the internal surface of the pipe, while non-intrusive methods can be mounted on the component which is to be monitored.

X.6.3. Infrastructure and construction

Corrosion monitoring of large structures such as bridges, tunnels, chimneys, etc., for safety and maintenance considerations is an essential requirement in today's world. These structures are often situated in harsh atmospheric conditions and, thus, at higher risk of corrosion (Zajec et al., 2018). Large structures are often constructed as composite structures of Steel reinforced concrete in the ground and thin-walled steel structures exposed to the atmosphere providing highways and tunnels for road traffic, railway, or underground transportation. Steel structures are protected from corrosion by properly formulated surface coatings. These surface coatings can degrade over time due to various environmental factors such as UV radiation, moisture, and corrosion, leading to anticorrosion layer break up and corrosion initiation on the substrate steel.

To prevent major accidents, safety regulations and acts of government authorities placed stricter requirements on access to corrosion monitoring for large structures. Access to large structures is time-consuming and often required expensive scaffolding and cranes. With the miniaturization of sensor technology and identification of new sensors, wireless sensor networks were found to be the best solution for corrosion monitoring on large structures. The early stages of WiSeNet for corrosion monitoring of steel structures are presented. The corrosion sensors based on eddy currents with a sensing region >50 cm^2 were developed with a sample rate of 1 per 3 min.

The sensor was tested in a newly constructed overpass top coating at the experimental field. Permanent installations of corrosion sensors and test coupons at the north side of the bridge were done in the summer of 2016. During the first summer of measurements, the sensor detected the coating degradation, and maintenance works were conducted based on the results of monitoring. The monitoring at the overpass is still ongoing. The designed sensors for corrosion monitoring of large steel structures are based on portable instrumented coated steel panels. The sensors detect the anticorrosion coating degradation on the steel structure anticipated from inspection and maintenance reports. The sensors were tested on some vehicles undergoing maintenance.

X.6.4. Automotive sector

Corrosion in the automotive sector is one of the most concerning issues for both customers and manufacturers. This major concern accounts for huge costs in the inspection and maintenance of corrosion in vehicles. Corrosion is a serious problem for nearly all types of metallic parts in the automotive sector, including axle, wheels, suspension parts, exhaust systems, springs, fuel pipes, tanks and bodywork. Also, in automotive non-metallic parts glued to metals, corrosion of the adhesive could result in the detachment of these components. The automotive sector involves a huge deduction of costs in the inspection methods being used. Cars are regularly monitored for corrosion around five years after their production date. This results in multi-million costs on account of labor, capital and major constraints in the fabrication/production of vehicles. The costs in such constraints are phenomenal. Accelerated lifetime tests are devised to shorten the waiting period but during this duration cars are put at risk, which could result in huge costs incurred on the grounds of human life, environmental pollution and damage to property.

The big worry for the automotive sector is the phenomena purely accounted for in the figure in the centre and it attracts a significant percentage of patents for corrosion monitoring. Corrosion accounts for a large percentage of failures in structures. The figure clearly states that corrosion monitoring is a big worry for industries. Monitoring is defined as the continuous data acquisition on the state of the component/structure/plant. It is event/parameter driven and the output comprises continuous data regarding the status of the component/structure/plant. The monitoring of vehicles is done for general concerns like system checkup, but lining inspection mainly concerns local damage monitoring. Lining inspection of vehicles concerns corrosion classified by the length of the inspected structure. No monitoring technique or system has so far been devised which could classically classify lining faults in vehicles.

Thickness loss due to corrosion on account of a particulate deposited on pipes can lead to catastrophic consequences if not detected in time. This is a big worry for the pollution/rescue control departments and a lot of patents are received for this subject. Corrosion monitoring in exotic industries like the oil and gas sector is a topic of human life losses. Economic and environmental losses are enormous in oil and gas incidents. Such expenses are unbearable in today’s economy and are highly disconcerting issues. The need for detection of corrosion at an early stage is a concern for the safety of the plant and lives in it. In this case, a continuous monitoring technique is a big boon to the industry.

X.6.5. Case studies in corrosion monitoring

Corrosion is a remarkable technical issue that influences various economic activities. Close to 3.5% of the world economy is jeopardized due to corrosion issues, including resource harbors, open tanks, pipelines, etc. Pipelines manage countless items with exceptional attentiveness due to the risk they pose to human life and the environment. Therefore, pipeline oversight is one of the most complex activities in material protection. Pipelines are seen as "big pipes". Nonetheless, leakage and ruptures are widespread occurrences within the Pipelines domain. Motivated by the drastic safety nature of pipelines and demanding protection practice, as well as the substantial economic costs for leakage catastrophes, a monitoring system that can detect corrosion states of buried pipelines is put forth. Agitated by electrical variations, pipelines operate as cathodic protection systems, sending a remarkably low current flow for millions of piping meters that are buried in the soil.

Pipelines are turned into monitoring areas in which short monitoring samples are changed into predictive, discrimination, and communicative models using chaos patterns. The first experimental demonstration of power-line-medium chaos-exploring corrosion monitoring is submitted based on a few practices. Major turbulence-induced data extraction methodologies and predictions helper models are archived, leading chaos-based state-discriminative and chaos-based corrosion-predicted forecasting at 1.24mm corrosion change. By maintaining this amplitude, a 10-years maintenance period of uncertainty should be recommended (Komary et al., 2023). By burying a few gold-coated short monitoring samples at the tangential direction of pipelines, weather change as well as absence supervision may drop to mere monitoring costs.

Surging with ambient AML chaos in pipelines, the patterns of monitoring samples will change toward complex chaos. An experimental methodology based on low-cost hardware is put forth to transform the descriptive form of advanced chaos into a predictive and state-discriminative form. Natural ambient chaos is further engaged to enhance long-distance monitoring efficiency. Those Nonlinear predictive methods are ameliorated to monitor corruption of a variety of shapes, types, and scenes. Witnessing predictions, piezo-sensors, gold-coatings, and even crazing chaos lines in multiplexing DOM are demonstrated to monitor corrosion of pipes and massive structures. Expected precision at the level of forecast errors down to mere 1.24mm is demonstrated by low-cost complaints. Insensitivity to external noise enables automatic measurements for all non-metal surfaces with environmental predictions. Agile employment is demonstrated by monitoring auxiliary coloring change in a corner pipe plot. This technology correlates with deeper monitoring and a broader inspection domain.

X.6.6. Case Study 1: Oil Pipeline monitoring

Corrosion is one of the major problems associated with oil production, processing and transportation. It poses significant threats to the structural integrity of pipelines and other facilities, and it is a leading cause of maintenance costs and environmental pollution. Consequently, reliable methods and techniques for corrosion monitoring and prevention are essential to successful and efficient operation of the oil industry. Corrosion monitoring techniques in the oil industry can be divided into two broad categories based on whether they can measure the corrosivity of the process media or whether they can measure the rate of corrosion reaction. A large variety of techniques are currently used for corrosion monitoring applications. Corrosivity monitoring cannot directly measure corrosion rates but is useful for on-line corrosion monitoring as an alternative to other techniques that are more expensive or difficult to implement. Most of the techniques can be exploited for oil production and processing. However, further developments may be required prior to implementation for gas transmission and distribution pipelines.

In particular, many of the techniques need to be made simpler and less expensive prior to industrial application for downstream processes. It is envisioned that in the foreseeable future, a variety of these techniques can be implemented for the indirect assessment of installation and effective control of corrosion rates in oil and gas infrastructures (Oki et al., 2013). Nevertheless, the application of such techniques to obtain a corrosion map of a specific pipeline will be prohibitive in terms of involved costs and time because it will require deployment of hundreds of sensors measuring the corrosivity factors. This is especially problematic in view that corrosivity monitoring cannot be done at points along the pipeline without prior installation of the corrosivity sensors. The ideal sensing solution must possess the following characteristics (Lawand et al., 2017): The sensor must not require a continuous power supply. The sensor must not interfere with existing pipe structure. Installation and replacements costs must be low. The proposed sensor system consists of a polymer sensor deployed on a pipe and a detector mounted on the pipe. The sensor reads the steel pipe potential continuously. The system yields a solution that overcomes the four challenges unique to pipelines.

X.6.7 Case Study 2: Bridge structural integrity

Corrosion Monitoring of Steel Structure Coating Degradation

The monitoring of coastal infrastructure has become increasingly important due to the deterioration of aging structures (Zajec et al., 2018). One monitoring technique involves assessing the condition of structural coatings, which is crucial in extending the lifetime of structures. An important feature in corrosion monitoring tasks is the ability to record and analyze corrosion data automatically and regularly. A robust, very low-power hardware architecture extensively tested and validated in practice for autonomous operation was developed in combination with an analysis algorithm and user-friendly software solutions. White paint coating has been selected with all tests performed in salt fog ambiance simulators. Multiple scenarios have been used, including immersion in 0.5 M NaCl endpoint of the test, and various points of interest have been targeted.

The subsequent topics include the description of a corrosion monitoring device system functioning on the principle of impedance measurement of capacitive elements, a technology description and its applications based on several case studies, and development of additional measurement cells for working with different coating types. A presentation of developments of an algorithm for autonomous monitoring along with test results and external impacts analysis will be showcased.

Structural integrity monitoring of bridge structures is a crucial task undertaken by civil engineers and structural health experts. Traditionally, vibration-based monitoring is adopted where one or several sensors are installed on the bridge structure and their measurement data is sent to a remote server for processing. This server-side processing, which may run complex algorithms to search for damage, overload, etc., may take up to several hours to complete, delaying the assessment of a monitored bridge's conditions. Recent advancements in deep learning present new methods of processing these vibration signals. Utilising deep learning, it is possible to extract features from raw time-domain measurements automatically and therefore the requirement for pre-processing the data is eliminated.

In recent years, there has been increased interest in operational-vibration-based monitoring. In this approach, a filtering technique such as wavelet-based digital filtering is applied to isolate the bridge's operational vibrations from other noise sources such as wind or traffic. By analysing only the noise-free operational vibrations, it is possible to more accurately identify the bridge's modal properties, a key indicator for assessing bridge safety. Along with model-space-based algorithms, data-driven algorithms such as those using deep learning represent another major category of structural monitoring methods. Combining vibration measurement, data preprocessing, feature extraction, and model training, fully data-driven machine-learning algorithms can be trained to assess a bridge's modal properties from raw measurements automatically.

X.6.8. Case Study 3: Marine vessel maintenance

A study was conducted on the feasibility of having a structural monitoring system on board vessels for proactive detection of corrosion in bilge/water ballast tanks and failure of protective coatings to protect metal substantially from corrosion. An innovative low-cost, fibre optic, and wireless corrosion monitoring device (CW2OP) developed by an international consortium was deployed in a bilge water tank of a FiCon vessel in service with Louis Dreyfus. The monitoring system comprised a portable wireless device to which 12 sensors were connected through 4 fibre cables. The portable device, after starting the monitoring function, continuously read temperature and corrosion rate values of transmission. After three months of coastal and harboured operations, data were captured and made available for evaluation. Results showed continuous monitoring provided better insight into the condition of the structure than periodic inspections (Latif et al., 2020). One of the major advantages of being proactive allowed the timing of repairs to take place with less loss of service and more cost-effectively. In addition, the important operational issue of ballast water management could be closely monitored with respect to the potential for causing surface coatings to fail. Holistically, the AMCM technology has the potential to improve maritime safety and reliability, the performance of structural assets, together with reduced OPEX and maintenance costs, and closure of some safety risks.

Over the years, corrosion monitoring has progressed from cumbersome traditional measurement devices such as weight loss coupons to simple-to-use sensors that can be connected to mobile devices. However, the straightforward measurement of corrosion rate alone may not successfully complete the task of corrosion monitoring for a critical engineering structure, as there may be unexpected failure modes that would not be captured or predicted from the simple corrosion rate data alone. A sophisticated corrosion monitoring system should also include coating monitoring and integrated structural health monitoring in addition to corrosion monitoring (Wasif et al., 2023).

X.7. Regulatory standards and guidelines

The alarming results of the devastating actions of corrosion initiated a rapid selection of corrosion codes, standards and guidelines to assist management of corrosion problems. These regulatory guidelines provide regulations, and code and standards documents on corrosion, corrosion protection and prevention in various sectors. Standards on corrosion control in boric acid systems, in service inspection of borated water storage tanks disregarding corrosion, et cetera were developed. The Petroleum and Chemical Industry standardised codes to tackle corrosive metallurgy with pipe insulation systems to minimize condensing vapor due to corrosion, extensive distribution avoiding ruptured pipelines. For the energy sector, standards and codes were accepted for the management of hot corrosion in coating and fouling under refractory lining. Finally, for the power plant components, dormant corrosion failures rejection thresholds and inspection intervals under a regulated plant life policy structures were put in place, whereas further evolving regulatory strategies were developed. The below sections provide a brief summary of the intent of the specified code and standard documents.

In the energy and power sectors, corrosion monitoring is tightly regulated by codes, industry standards, and approaches. Examples are codes to avoid corrosion under insulation and to monitor external corrosion of buried and underground piping, piping inspection portions of overall corrosion monitoring programs to be implemented by plant licensees, and additional codes, standards and guidelines to monitor corrosion fatigue of plants, allied industry raise awareness of corrosion problems. Corrosion management is mandated by a gradual rollout of guidance on integrity assessments. In summary, the demonstrated awareness and active steps taken to protect vulnerable applications and components, and the establishment of corrosion regulatory standards and guidelines, could serve as a template for other applications sectors similarly prone to corrosion such as the energy supply industry because it is equally critical for humankind.

X.7.1. ISO standards

The International Organization for Standardization develops, publishes, and globally recognizes standards according to which the content and rules for the delivery of documents are established. The aim is to facilitate market access for the homogeneous protection of health, safety, security, and the environment. In the context of corrosion monitoring, ISO documents are important guidelines for the manufacturers, operators, and test institutes of corrosion monitors. Corrosion monitoring standards provide rules for set-ups, modes of operation, data evaluation, and specification of the amount and type of data to transmit. The application of these standards is important for the characterization of corrosion monitors and also for the assessment of the applicability of the devices to a specific monitoring task.

One standard outlines different definitions of the terminology employed in corrosion monitoring. Terminology relevant to passive and active corrosion monitoring, types of external media, protective devices and measures, tests, and references is also addressed, along with terms related to test methods and test reports and different aspects relevant to the evaluation and performance testing. This part is relevant to associated standards that concern monitoring equipment, protocols for operation and requirement for validation and performance testing.

Passive/cavitating devices, which were most useful for monitoring non-aerated groundwaters or closed systems, suffer from the limitations of being slow-responding and information-limited devices. For monitoring the performance of external corrosion protection systems, the more common uses involve buried steel pipelines in soil-electrolyte conditions, subjected to cathodic protection by current-passing electrodes. Factors relevant to the application of these probes, recognize merited caveats relating to their ill-use and misinterpretation of data, are reviewed. Two monitoring instruments widely used, which are based on the assessment of time-resolved signals indicative of corrosion product formation and inhibition response transients, are briefly described.

X.7.2. ASTM guidelines

Two underregulated testing methods were analysed, and basic guidelines for the appropriate application of the two methods were set. It was clearly demonstrated that performing atmospheric exposure tests on specimens that cannot be analysed in a time frame of days or weeks using normal standards limit the applicability of most testing methods. Therefore, two additional approaches have been used to assess some of the required information on the atmospheric corrosion parameters. First, a galvanic cell sensor measures the corrosion rate of metal coupons exposed to the atmosphere. The sensor is an electrochemical sensor composed of several mounted pairs of galvanic cells. The corrosion rates obtained by these sensors were used to estimate the maximum amount of carbon steel area lost. Second, approximately five years of continuous high frequency noise measurements were analysed to observe possible atmospheric parameters effect on the intensity of the corrosion process.

Weather conditions are the first atmospheric parameters that influence atmospheric corrosion. The direct contact of the likely corrosive combination of water and pollutants is a necessary condition for the corrosion to start. Wind speed, number of wet hours in a day, and number of rainy hours significantly affect the corrosion levels of both metals. In some cases, solely one of these predictors has a big enough impact that caused sharp changes in the corrosion levels in the long time period that has been assessed. This has also been carefully analysed. One thing that would help with these analyses is if information on the amount of rain and humidity could be added to the already existing wind speed information. Then a better estimate of which range of wetness causes a change in the corrosion progress velocity could be made.

Overall, both the testing methods and the assessment methodologies can provide close to the information gained from the standard methodologies, especially considering that the alternative approaches to determine the corrosion rates of metals exposed to the atmosphere have very limited availability compared to the methods used in this study. Using the corroded surfaces to assess the maximum amount of corrosion has opened plenty of avenues for further research in areas that have been very little studied. A possibility of such long term tests on small specimens with crude testing methods has been demonstrated.

X.7.3. Industrybest practices

Corrosion is an electrochemical phenomenon that occurs on metal surfaces and is accelerated by heat, moisture, humidity, and pollutants, reducing the life expectancy of metallic structures. Building materials are the basis of major investments in construction, energy, transport, infrastructure, production, and so on. Corrosion monitoring is the simplest approach for corrosion control since it can be used both directly, for example, to measure corrosion rate or detect corrosion, and indirectly for ascertaining the state of structures, e.g. stress, strain, and permeability. It can also be used for preventative measures by initiating cathodic protection, controlling moisture, or applying a protective coating. A general corrosion monitoring setup consists of a group of detectors that measure desired corrosion indicators such as current, voltage, capacitance, mass loss, potential, or frequency. This data is sampled and filtered by a microcontroller to be stored in EEPROM. After connecting to a network, the controller can send the data via Ethernet, 3G/4G, RS232, or RS485 to a computer, which runs a program. The program assesses the corrosion state of the structure and its components and allows the user to visualize the results continually and in real time.

Metal coupons are one of the most widely used and reliable types of detectors. Coupons are exposed to corrosive conditions at predetermined locations on the structure or component. They are later removed, degreased, and cleaned in a series of acid and solvent baths, and the change of weight and thus corrosion loss is determined gravimetrically or electrochemically by mass gain, or decrease of corrosion products. Coupon detectors can thus be employed for detection of rainfall and/or moisture ingress in corrosion based monitoring applications. Electrochemical sensors detect local corrosion indications such as current, voltage, capacitance, impedance, or frequency. They continuously or semi-continuously transmit this corrosion information to the computer system, which assesses the results. In many cases, the computing unit, e.g. a computer or a PCB with a microcontroller, is on-board with the detector. Detection and monitoring of cathodic protection is also possible. CP detectors measure potential difference between the structure and the reference electrode, which shows the structure’s CP state, and/or the amount of current flowing into the structure to assess protection against flow.

X.8. Future trends in corrosion monitoring

As an energetic discipline evaluating the integrity of structures, corrosion monitoring technologies and applications are discussed. Since corrosion is inevitable, continuous monitoring of structures is essential in order to prevent personal injury and property damages. The monitoring techniques available are displayed, tabulated, and categorized in terms of two techniques, direct and indirect monitoring techniques concerning ages and technology levels, and their monitoring principles are briefly explained (Wasif et al., 2023).

Different structures and sites were presented in which corrosion monitoring has been used. These examples cover the structures that have various human activities and are naturally and anthropogenically accelerated corrosion. This paper hopes it will guide researchers to choose the appropriate monitoring techniques for their corrosion problems. Finally, it is suggested to monitor steel corrosion rates in buildings, bridges, etc., as well as reinforced concrete structures and underground structures with a smart corrosion monitoring and control system.

Corrosion measurement is carried out using a set of detectors, data storage and transmission systems, and corrosion information interpreting software. With detectors, corrosion weight loss, corrosion rate, and pH of the solution can be measured; then the information is conveyed to a computer system for further interpretation, phone or report text generation, and API output for other applications (Komary et al., 2023).

Metal coupons are one of the most widely used and reliable methods for corrosion detection in different industries. While corroded metal coupons provide information on coupons' location, the metal material, exposure time, and type of the analysis performed. Various processes have been developed to determine OCP, polarization resistance, and other parameters. Recent advances in these techniques provide the ability of inline measurements and real-time data acquisition. Although metal coupons have various advantages, corrosion monitoring using metal coupons does not provide a real-time measurement. Furthermore, the transmission and analysis of captured images usually happen in hours or days after the analysis, thus preventing corrective actions in a timely manner.

X.8.1. Innovations in sensor technology

Sensors are used to measure physical parameters, including temperature, pressure, pH, vibration, flow, level, moisture, humidity, and gas content. Numerous sensors can be combined together to create a sensor network system with a smarter computing platform, which will improve quality and process control and increase productivity in aggressive environments. Sensors for corrosion monitoring were developed to monitor the monitored framework's state. Corrosion monitoring sensors work on the basis of voltage/potential measurement, acoustic emission measurement, detection of product evolution from electrodes (cavitation, induced hydrogen, gas evolution), impedance measurement, pH, and ion concentration measurement. The prominent parameter is voltage, and corrosion rate can be determined based on the obtained value.

Environmental parameters such as humidity and pH play an important role in corrosion, therefore optical fiber sensors such as fluorescence or colorimetry are widely used for monitoring these elements. (Komary et al., 2023) developed novel low-cost systems based on the combination of type 1 and type 4 measurements using LPG sensors in order to detect both the strain and environmental parameters and therefore obtain better corrosion data on the analyzed structure. The developments in the whole SBAS architecture are described, where its capabilities are demonstrated with a synchronization experiment on a chemical plant and a bridge. It would be good to see results obtained from other more harshly operated structures, for example regarding weight of the sensors, it would be good to mention how the sensor nodes' weight could be reduced.

Ultrasonic corrosion monitoring is a type of non-destructive testing (NDT) that is used to track the corrosion process. High-frequency acoustic waves are used in this monitoring technique to measure the interior structure, thickness, and other properties of the material being monitored. Therefore, publications that presented low-cost corrosion monitoring solutions for various industries based on ultrasound technology are reviewed. A novel corrosion control method has been created for protecting damaged, painted surfaces in contact with atmospheric conditions, employing electromagnetically induced surface currents (EISCS). It can avoid corrosion as EISCS generates a little cathodic current to mitigate the anodic ones, thereby preventing intense corrosion. The method is being proposed in hybrid solutions supporting active and passive corrosion control in the same environment. Environmental pollution interferes with the quality of the environment and human health. Several scholars have introduced monitoring sensors based on Faraday's law of electromagnetic induction (EMI) for the early assessment of corrosion in reinforced concrete structures. Accurate and timely assessment of safety status and deterioration of infrastructure is currently one of the most crucial challenges. Recently, the demand for low-cost systems to monitor corrosion in reinforced concrete structures has increased as several countries have many uninspected critical infrastructures. These structures can be more sensitive to external environmental factors, and their deterioration mechanisms can be very complex.

X.8.2. Integration with IoT

The corrosion monitoring process can be divided into the following steps: detection of corrosion, data storage and transmission, processing and analysis of the detected data, assessment of the corrosion state of the structure and its components. Each of the above-mentioned aspects in corrosion monitoring is a very important task on its own. Numerous techniques based on chemical, electrochemical, physical, and/or acoustic measurement principles have been developed and used for corrosion detection. Detection technologies use a set of detectors to identify the corrosion process occurring in the structure. These detectors range from custom-made one-off designs to commercially available detectors, which can be used in a distributed arrangement. The primary function of these sensors/monitors is to collect indicators of corrosion activity, which are then processed using different means in order to gain insight into the corrosion state of nature and quantity of the monitored structure. Monitoring decision needs to take into account all available information. It indicates which targets/areas/subzones are potentially at risk or undergoing changes in their state (Komary et al., 2023). In addition to the corrosion detection stage, corrosion monitoring necessitates various functions associated with detected data storage/transmission, acoustic detection data processing/analysis, and corrosion assessment. Information storage is usually ensured by a local data storage device that stores and preprocesses the monitoring data and delivers it to the corrosion monitoring server. Portable hard drives, standalone computers, mainframe computers, and servers are sometimes found as local data storage devices. When transmitted to the server, data can initially undergo storage and preprocessing and can be subsequently presented as processed information concerning corrosion activity and corrosion loss assessments. Information is very commonly stored in data databases for later access by corrosion engineers. The implementation of corrosion mapping can pose an additional burden on data communication. All types of detectors, kinematics, and application domains of detection systems may theoretically be found.

X.8.3. Predictive maintenance strategies

The randomness and uncertainty existing in real-world mechanical systems call for robust predictive maintenance strategies. Estimating remaining useful life (RUL) in quantitative fashion is considered a more sophisticated condition assessment approach to prevent failures and losses (Latif et al., 2020). While this is a mathematically involved problem with many attempts to solve it for different degradation patterns, the focus of this paper is on continuous structural health monitoring (SHM) systems where defenders observe corrosion formation and propagation via corrosion monitoring methods. Instead of determining RUL, defenders patch the growth of defects by determining the status of corrosion monitoring sensors deployed on the structure as either active or inactive. The two methodologies for prediction of sensor status are: a detection-based approach that generates a count of the number of active sensors based on the sensor observations; and a model-based approach that tracks the status of each sensor explicitly over time. The detection-based approach treats the sensor observations as outliers when estimating the system state and its performance deteriorates with increasing number of faulty sensors. The model-based approach reduces uncertainty in the state of each sensor independently and incrementally learns the state of the sensors with promising performance. Variable monitoring frequency is also desired from practical points of view such as reducing maintenance cost. The RUL estimates by commonly used probabilistic methods with a time interval depend on the uncertainty of the statistics of the variables involved. However, with too many observations and either already deterministic or more deterministic variables, the RUL estimates will fall short of the practical needs for sub-optimal maintenance timings.

X.9. Conclusion

Corrosion is a universal process that gradually deteriorates the quality of structural materials used in industries. Various industries such as oil and gas, aerospace, ships, and power plants spend billions of dollars on corrosion control every year, making it one of the most critical concerns in safety and economy worldwide. Corrosion monitoring is the determination of the corrosion process by which the time, location, and magnitude of the corrosion in the monitored area are comprehensively evaluated over time. Many traditional techniques for corrosion monitoring do not deliver real-time measurements, which have made electronic corrosion sensors critical in recent decades. Despite their massive development, there are still performance and reliability gaps in comparing with conventional techniques. This review aims to provide a comprehensive overview of corrosion monitoring to non-expert readers, address current challenges and obstacles, and outline development paths towards new possibilities in corrosion monitoring. The first section introduces the basic concept of corrosion monitoring. The second section presents various low-cost technologies applied in the industries. The third section summarizes knowledge gaps of low-cost technologies, along with possible directions. It is hoped that this can foster the research and commercial applications of low-cost technologies in corrosion-monitoring applications across different fields.

Corrosion is a naturally occurring process in all materials and structures, making corrosion prevention a top priority. With elevated rates, corrosion may cause platform failure and closure, leading to worker injury, environmental impact, and costly repercussions. Significant research has been conducted to investigate long-term and short-term corrosion products, controls, and management strategies. However, laboratory tests often disassociate strong environmental variables and only examine individual corrosion processes in a highly controlled setting, resulting in poor correlation to field conditions. Various tests are utilized to quantify and monitor real-time conditions in a laboratory setting, typically involving electrical signals measured as voltage or current. Reference electrodes and electrical noise measurements can also perform similarly under high-stability conditions. However, relatively few tests can characterize corrosion responses in the field. Stress-corrosion testing using strain gauges is widely adopted in commercial applications but cannot be continuously or conveniently monitored. Corrosion sensors are sensitive to low corrosion rates but are application dependent, and there can be performance variations due to environmental and surface conditions. Smart pigging and time-domain reflectometry can be performed by physical professionals to provide high-integrity data and real-time feedback, but these commercially available technologies are expensive and schedule intensive.