ΕΘΝΙΚΟ ΜΕΤΣΟΒΙΟ ΠΟΛΥΤΕΧΝΕΙΟ
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ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ
ΧΡΙΣΤΟΠΟΥΛΟΥ ΓΕΩΡΓΙΑ

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ΕΘΝΙΚΟ ΜΕΤΣΟΒΙΟ ΠΟΛΥΤΕΧΝΕΙΟ
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Είδη διάβρωσης και μέθοδοι προστασίας σε θαλάσσιες κατασκευές (offshore structures)

ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

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ABSTRACT

The aim of this diploma thesis is to study the corrosion effect on offshore structures as well as the methods of corrosion protection. The causes and mechanisms of corrosion, the types of corrosion in oil and gas platforms and the corrosion control are analyzed. More specifically, the coatings and the methods of cathodic protection are described in depth and the conjunction of coating with cathodic protection is investigated.

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Contents

1 OFFSHORE STRUCTURES

The first chapter refers to offshore engineering and described the different types of offshore platforms based on water depth requirements, geometry and installation concepts.

1.1 The offshore oil and gas industry

One of the greatest discoveries of 20th century was oil and it has so many applications that it cannot be separated from mankind. The oil exploration has started as early as 1900 and the oil exploration initially was concentrated on land. As the need for oil expands in an explosive rate, need for find new discoveries was eminent. During the middle of 20th century, oil discovery started in near shore and medium range of water depth. The need for qualified offshore structural personnel are rapidly increasing as the oil industry moves into deeper water in the search for additional supplies of oil and gas, new technology is emerging at a rapid peace for the development of new concepts for offshore platforms.

1.2 Types of offshore structures

The offshore structures build in the ocean to explore oil and gas are located in depths from very shallow water to the deep ocean. Depending on the water depth and environmental conditions, the structural arrangement and need for new ideas required. Based on geometry and behaviour, the offshore structures for oil and gas development has been divided into following categories.

1. Fixed Platforms
    - Steel template Structures
    - Space Frame Structures
    - Concrete Gravity Structures

2. Compliant Structures
    - Compliant Tower
    - Guyed Tower
    - Articulated Tower

3. Floating Structures
    - Tension Leg Platform
    - Spar Platform
    - Floating Production System
    - Floating Production, Storage and Offloading System

1.2.1 Fixed Platforms

The fixed type of platform shall exhibit a low natural period and deflection again environmental loads.

1. STEEL TEMPLATE STRUCTURES

   The steel template type structure consists of a tall vertical section made of tubular steel members supported by piles driven into the sea be with a deck placed on top, providing space for crew quarters, a drilling rig, and production facilities. The fixed platform is economically feasible for installation in water depths up to 500m.

   These template type structures will be fixed to seabed by means of tubular piles either driven through legs of the jacket (main piles) or through skirt sleeves attached to the bottom of the jacket.

    - Monopiles: These consist of a steel pile that is inserted into the sea bed. Most of the existing deployments in waters under 65 – 82 ft (20 -25 meters) consist of monopile foundations (Figure 1.1). Their main advantage is that they are relatively easy and cheaper to manufacture and are easy to install. Their major disadvantage is that it cannot be used in waters more than 82 ft (25 meters) deep as it becomes unstable.

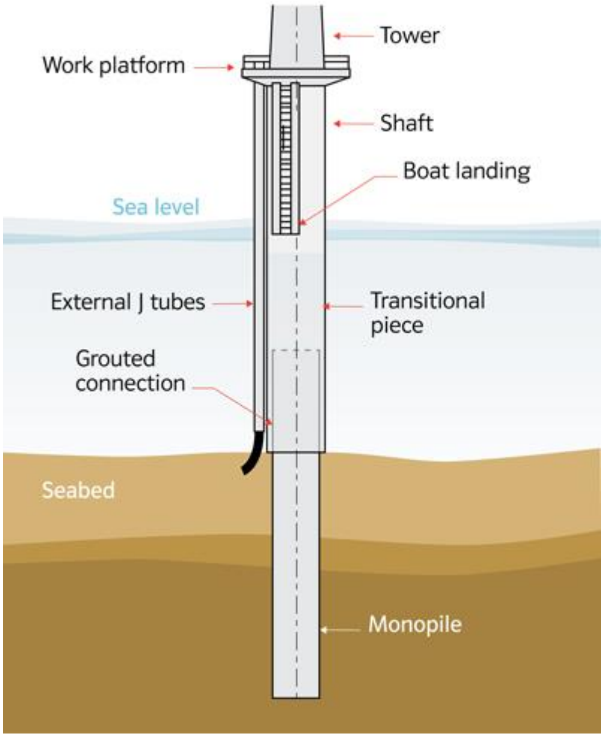

Figure 1.1: Monopile

2. SPACE FRAME STRUCTURES

   Even though today these are not heavily used they are considered for deeper waters. In the future, they are expected to be further developed and may be heavily used in future wind farms. Space Frame Structures come in three variations.

   - Tripods: The tripod, which is a standard three-legged structure that have a central steel shaft that is attached to the turbine tower (Figure 1.2). Similar to the monopiles, each leg is inserted into the sea bed, but together they form a much stronger structure suitable for waters 65 – 165 feet (20 – 50 meters) deep.

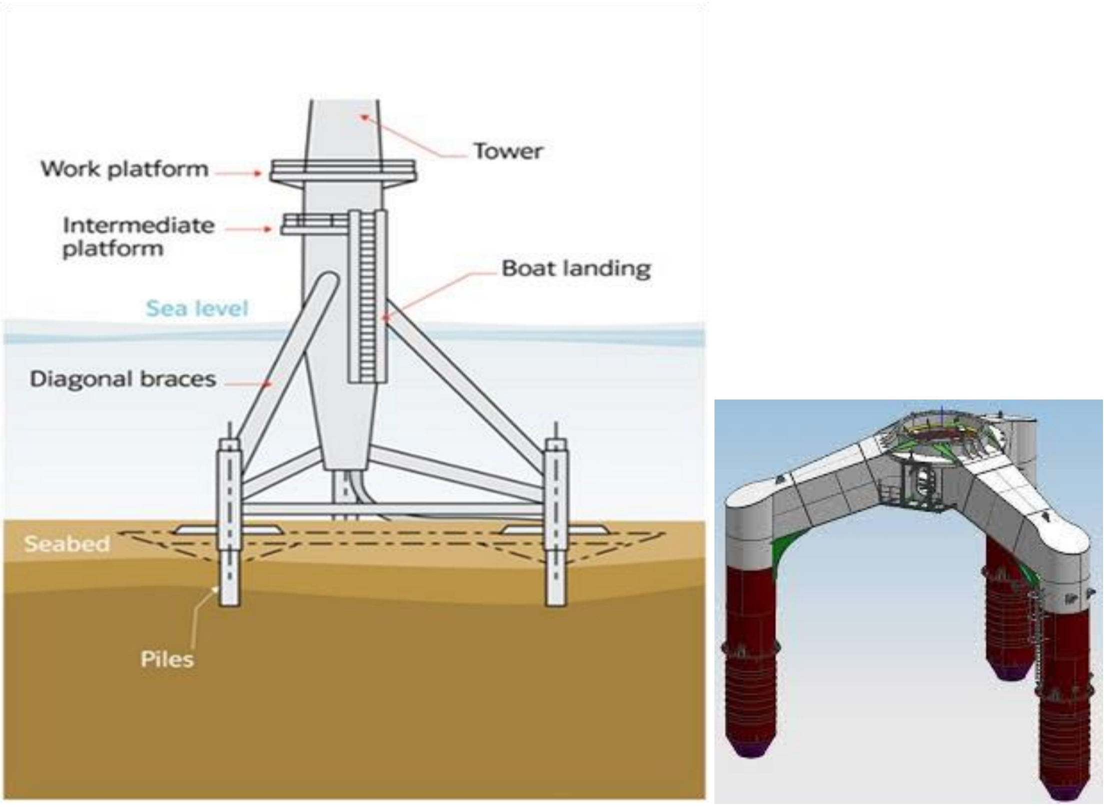

Figure 1.2: Tripod

- Jackets: Second the jacket, have a similar concept to the tripod but they differ in the fact that they consist of a larger plan area through the majority of the structure, allowing the steel shaft to be positioned away from the centre of the axis (Figure 1.3). This design results in considerable savings of materials. Similar to the tripod, each leg is inserted into the sea bed using piles.

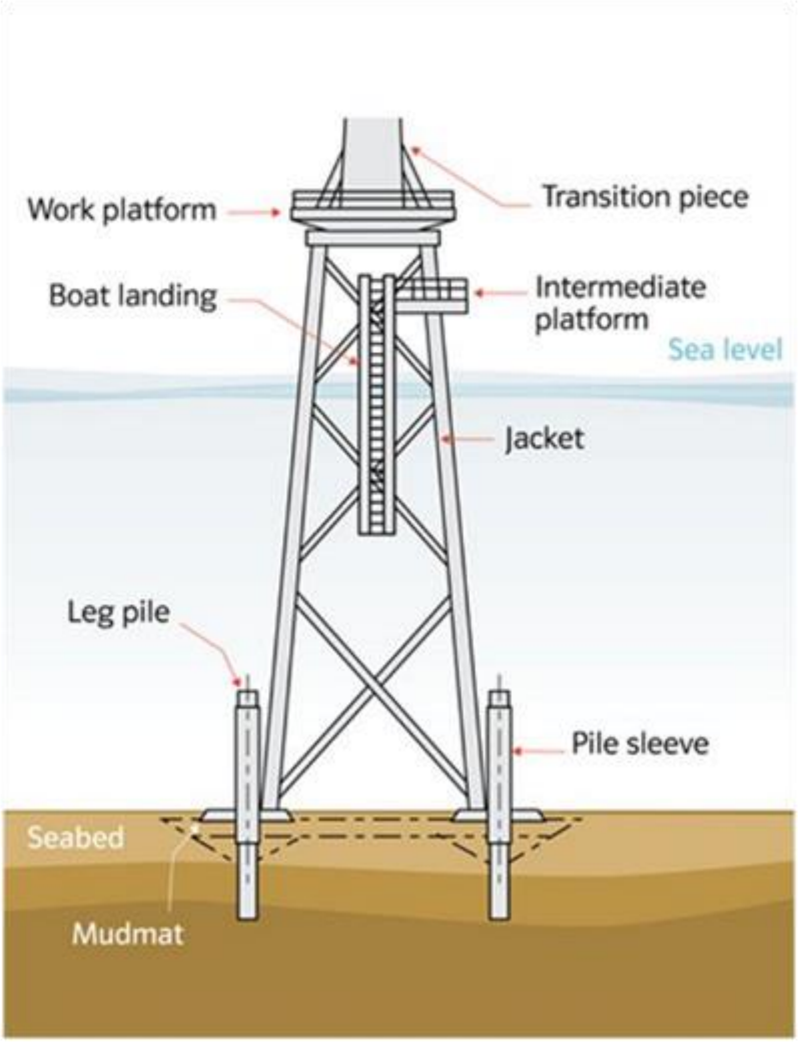

Figure 1.3: A jacket structure

3. CONCRETE GRAVITY STRUCTURES

Most of the remainder of today’s installations consist of Gravity Based Structures (GBS) which are also relatively easy to manufacture. As opposed to the monopiles, GBS are not inserted into the seabed but rather sit on the seabed. Their structure is filled with sand, concrete rock and iron in order to keep it stable. GBS are most suitable for depths up to 100 ft (30 meters).

Concrete gravity platforms are mostly used in the areas where feasibility of pile installation is remote. These platforms are very common in areas with strong seabed geological conditions either with rock outcrop or sandy formation.

Some part of North Sea oil fields and Australian coast, these kinds of platforms are located. The concrete gravity platform by its name derive its horizontal stability against environmental forces by means of its weight. These structures are basically concrete shells assembled in circular array with stem columns projecting to above water to support the deck and facilities (Figure 1.4). Concrete gravity platforms have been constructed in water depths as much as 350m.

Figure 1.4: Concrete platform

1.2.2 Compliant Structures

In addition to the developing technologies for exploration and production of oil and natural gas, new concepts in deepwater systems and facilities have emerged to make ultra-deepwater projects a reality. With wells being drilled in water depths of 3000m, the traditional fixed offshore platform is being replaced by state-of-the-art deepwater production facilities. Compliant Towers, Tension Leg Platforms, Spars, Subsea Systems, Floating Production Systems, and Floating Production, Storage and Offloading Systems are now being used in water depths exceeding 500m. All of these systems are proven technology, and in use in offshore production worldwide.

1. COMPLIANT TOWER (CT)
   A compliant tower (CT) is a fixed rig structure normally used for the offshore production of oil or gas. Compliant Tower (CT) consists of a narrow, flexible tower and a piled foundation that can support a conventional deck for drilling and production operations (Figure 1.5). Compliant towers are designed to sustain significant lateral deflections and forces, and are typically used in water depths ranging from 1,500 to 3,000 feet (450 to 900 m). At present the deepest is the Chevron Petronius tower in waters 623m deep. Unlike the fixed platform, the

compliant tower withstands large lateral forces by sustaining significant lateral deflections. The first tower emerged in the early 1980s, at present the deepest is Baldpate in 580 m of water.

Figure 1.5: Compliant Tower

2. GUYED TOWER

   Guyed tower is an extension of complaint tower with guy wires tied to the seabed by means of anchors or piles (Figure 1.6). This guy ropes minimizes the lateral displacement of the platform topsides.

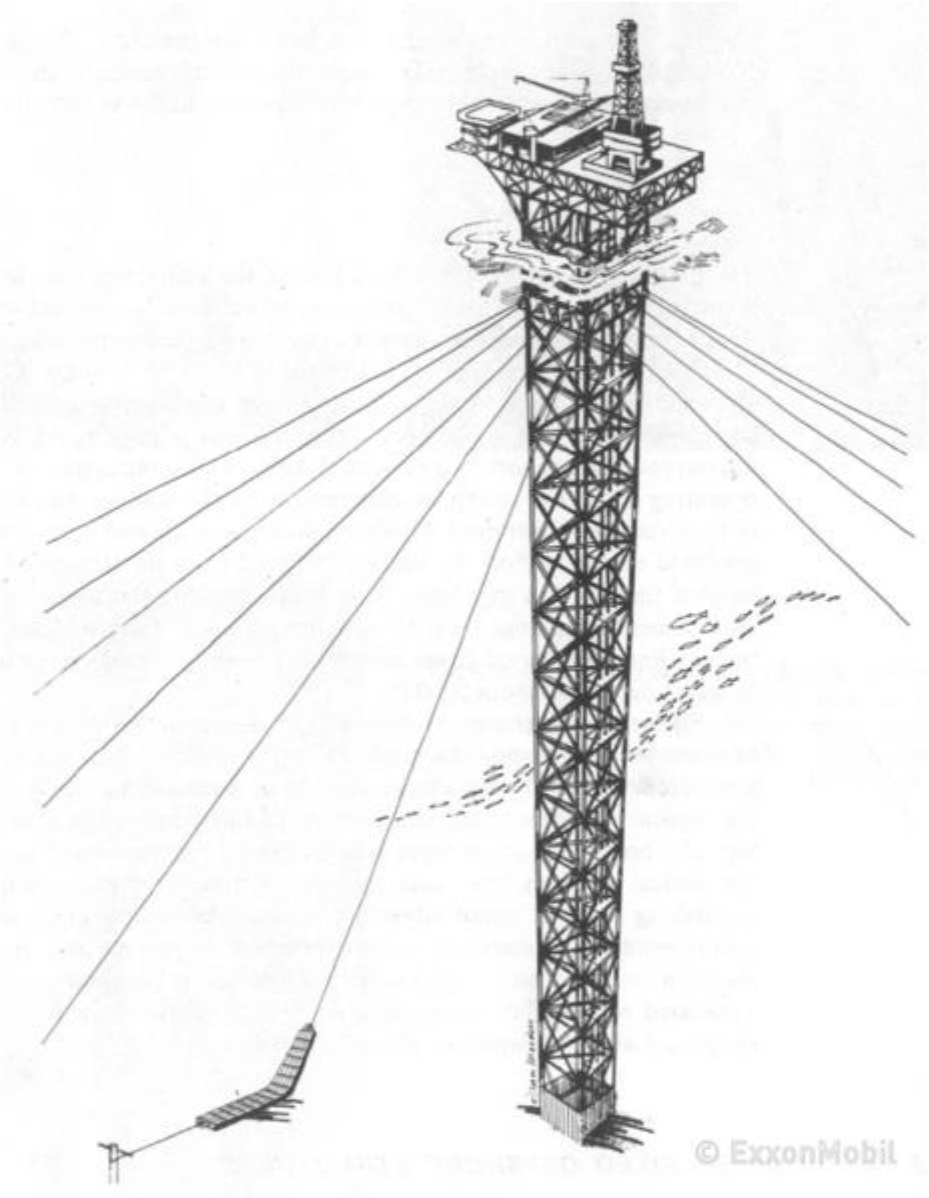
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Figure 1.6: Guyed Tower

3. ARTICULATED TOWER

   The articulated tower is an extension of tension leg platform. The tension cables are replaced by one single buoyant shell with sufficient buoyancy and required restoring moment against lateral loads.

   The main part of the configuration is the universal joint which connects the shell with the foundation system. The foundation system usually consists of gravity based concrete block or sometimes with driven piles.

   The articulated tower concept is well suited for intermediate water depths ranging from 150m to 500m.

1.2.3 Floating Structures

1. TENSION LEG PLATFORMS
   A Tension-leg platform is a vertically moored floating structure normally used for the offshore production of oil or gas, and is particularly suited for water depths around 1000m to 1200 metres (about 4000 ft). The platform is permanently moored by means of tethers or tendons grouped at each of the structure's corners. A group of tethers is called a tension leg. A feature of the design of the tethers is that they have relatively high axial stiffness (low elasticity), such that virtually all vertical motion of the platform is eliminated. This allows the platform to have the production wellheads on deck (connected directly to the subsea wells by rigid risers), instead of on the seafloor. This makes for a cheaper well completion and gives better control over the production from the oil or gas reservoir.
   Tension Leg Platform (TLP) consists of a floating structure held in place by vertical, tensioned tendons connected to the sea floor by pile-secured templates. Tensioned tendons provide for the use of a TLP in a broad water depth range with limited vertical motion. The larger TLP's have been successfully deployed in water depths approaching 1250m. The first Tension Leg Platform was built for Conoco's Hutton field in the North Sea in the early 1980s.

2. SPAR PLATFORM
   SPAR Platform (SPAR) consists of a large diameter single vertical cylinder supporting a deck. It has a typical fixed platform topside (surface deck with drilling and production equipment), three types of risers (production, drilling, and export), and a hull which is moored using a taut catenary system of six to twenty lines anchored into the seafloor. SPAR's are presently used in water depths up to 1000m, although existing technology can extend its use to water depths as great as 2500m

3. FLOATING PRODUCTION SYSTEM
   Floating Production System (FPS) consists of a semi-submersible unit which is equipped with drilling and production equipment. It is anchored in place with wire rope and chain, or can be dynamically positioned using rotating thrusters. Production from subsea wells is transported to the surface deck through production risers designed to accommodate platform motion. The FPS can be used in a range of water depths from 600m to 2500m feet.

4. FLOATING PRODUCTION STORAGE AND OFFLOADING SYSTEM

   Floating Production, Storage and Offloading System (FPSO) consists of a large tanker type vessel moored to the seafloor. An FPSO is designed to process and stow production from nearby subsea wells and to periodically offload the stored oil to a smaller shuttle tanker. The shuttle tanker then transports the oil to an onshore facility for further processing.

   An FPSO may be suited for marginally economic fields located in remote deepwater areas where a pipeline infrastructure does not exist. Currently, there are no FPSO's approved for use in the Gulf of Mexico. However, there are over 70 of these systems being used elsewhere in the world.

1.3 Types of offshore oil and gas installations

Extensive infrastructure is required to support the offshore production industry. There are more than 6500 offshore oil and gas installations in some 53 countries around the world. More than 50% of these installations are in the US Gulf of Mexico. The next five largest areas in descending order are Asia, Middle East, North Sea, West Africa coast, and South America. These six regions account for the majority of the existing offshore oil and gas installations. The installations are built for exploration (drilling) and production (including preparing water or gas for injection, processing oil or gas, cleaning produced water for disposal, and various accommodations).

1.3.1 Types of drilling rings

1. JACKUPS

   Usually towed to a location after which the legs are lowered to the seabed and the hull is jacked above the sea surface.

2. DRILL SHIPS

   They look like ordinary ships with a derrick on top which drills through a hole in the hull. They can be anchored or positioned with computer-controlled propulsion systems.

3. SUBMERSIBLES

   They can be floated to shallow water locations and ballasted to sit on the seabed.

4. SEMI-SUBMERSIBLES

   They have the superstructure supported on a hull or pontoons which are ballasted below the water surface. Today’s “deepest” semisub is Atlantis PQ (-2156 m).

Once the drilling rigs have completed their work, they are generally replaced by production platforms. Production platforms vary in size and shape, but generally contain accommodations for larger crews and the various production processes required to extract the oil or gas and render it suitable for transport. Sometimes smaller, satellite platforms will be situated around a larger production platform.

1.4 Deepest oil platforms

The world's deepest oil platform is the floating Perdido (Figure 1.7), which is a spar platform in the Gulf of Mexico in a water depth of 2,438 metres.

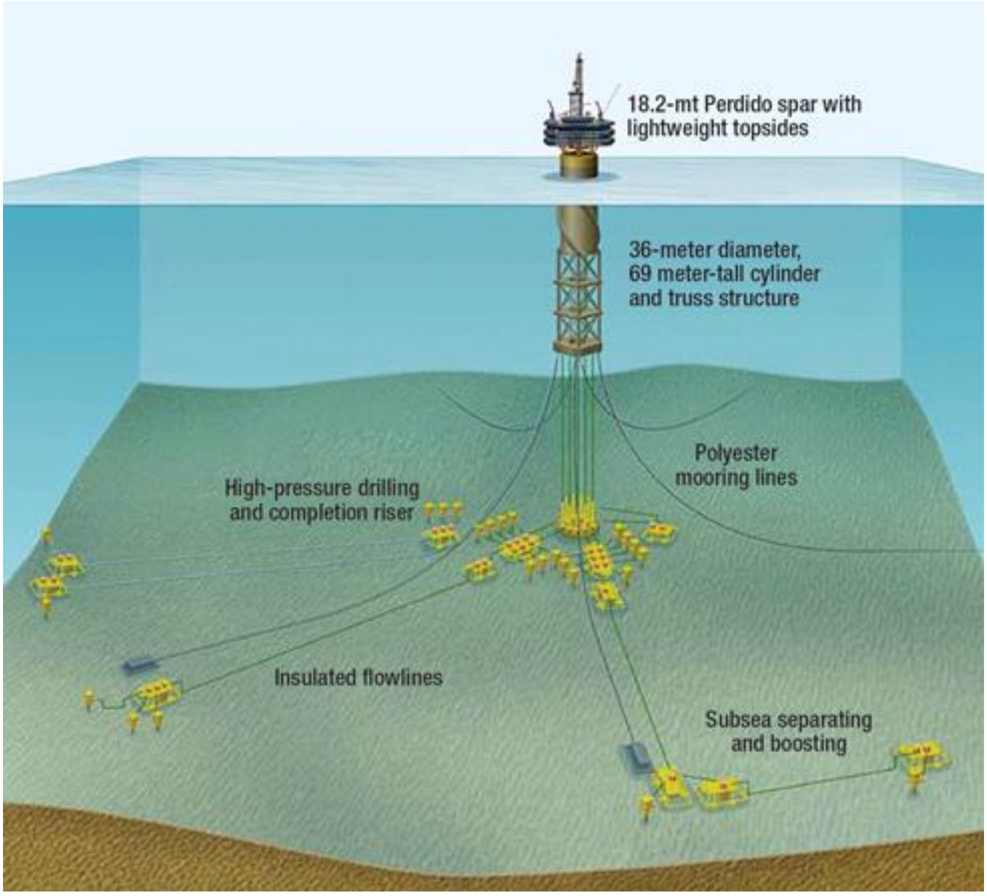

Figure 1.7: Perdido - the deepest oil platform

Perdido extracts oil from twenty-two oil wells and is connected a 27 mile (44 km) network of “umbilical” pipelines on the ocean floor which, in turn, connect with 4 risers that bring oil to the surface (Figure 1.8).

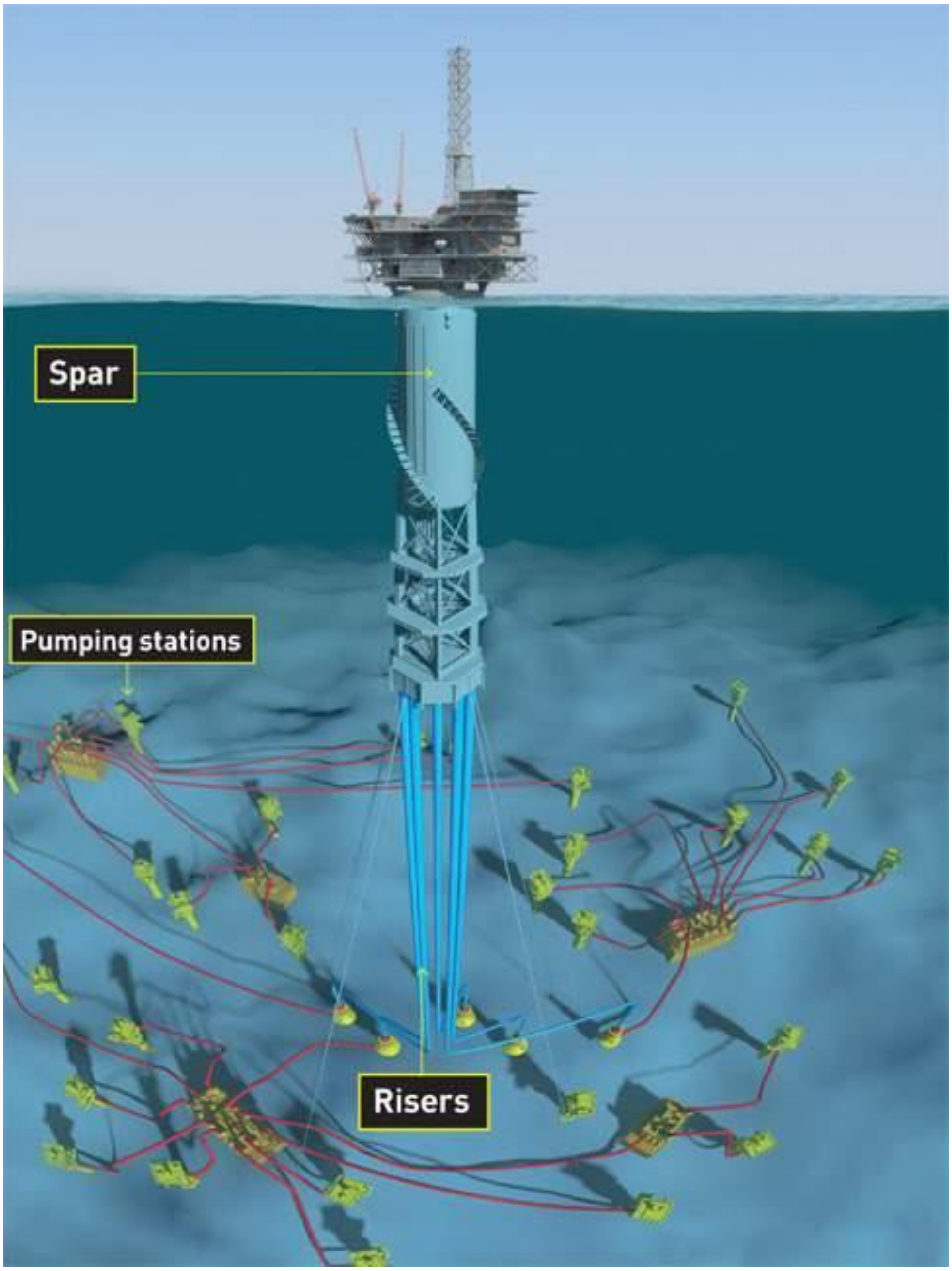

Figure 1.8: World's largest offshore oil platform, an engineering masterpiece

Non-floating compliant towers and fixed platforms, by water depth:

- Petronius Platform, 535 m (1,755 ft)
- Baldpate Platform, 502 m (1,647 ft)
- **Bullwinkle Platform, 413 m (1,355 ft)**
- Pompano Platform, 393 m (1,289 ft)
- Benguela-Belize Lobito-Tomboco Platform, 390 m (1,280 ft)
- Tombua Landana Platform, 366 m (1,201 ft)
- Harmony Platform, 366 m (1,201 ft)
- Troll A Platform, 303 m (994 ft)
- Gulfaks C Platform, 217 m (712 ft)

In 1978, Shell installed the Cognac platform in the Gulf of Mexico in three sections, excluding the deck. It sits on the seabed in 330 metres of water. The figure below (Figure 1.9) shows the Bullwinkle platform, which was installed 10 years later in 412 metres of water as a single section, excluding the deck module. This platform still holds the world record for the tallest fixed jacket structure ever placed in the sea: from the seafloor to the tip of the flare stack, the structure is about twice the height of the Eiffel tower in Paris The Bullwinkle platform is significant because it marks the limit of what can be achieved using traditional offshore technology. It heralds the beginning of a period when Shell and others in the industry advanced the frontiers of oil and gas exploration and production as never before.

Figure 1.9: The Bullwinkle platform in the Gulf of Mexico

2 CORROSION

The second chapter refers to corrosion in the oil and gas production industries and describes the major forms of corrosion in seawater. It analyses the three problem areas of offshore structures, atmospheric zone, splash zone and submerged zone and gives introduction to materials used for offshore structures.

2.1 General

Offshore structures involve massive investments, and they also pose potential risks for both people and the environment, if they fail. One of the potential reasons for the structures' failure can be corrosion, highlighting the importance of corrosion protection and its design.

Corrosion of metals is an electro-chemical process of loss of material from one location. This may get deposited in the same metal in another area. Corrosion in a wet environment attacks the metal by removing the atoms on the metal surface. The metal atoms at the surface lose electrons and become actively charged ions that leave the metal and enter the wet electrolyte. The metal ions join with/to oppositely charged ions from another chemical and form a new, stable compound. [8]

For offshore structures, the main form of corrosion is external corrosion. This corrosion distribution results from the external environment, and the reactions between the structural materials and the environment. [10]

2.2 Causes and mechanisms of corrosion

The high alkalinity (pH 12.5 - 13.5) of concrete causes the reinforcing steel to form a passivating film. There are two main mechanics that nullify the effects of the protective passivating film and lead to corrosion: carbonation and chloride contamination. [1]

Carbonation results from carbon dioxide diffusing through concrete and decreasing the alkalinity of concrete. Factors that influence the ability of concrete to resist carbonation are: adequate concrete cover, sound concrete with no cracking, high cement content and good compaction.

Chloride contamination attacks the passivating layer around the reinforcing steel but unlike carbonation there is less of a drop in pH. Chlorides can be cast into concrete or can penetrate concrete. Cast-in chlorides come from the addition of chloride accelerators, seawater, or contaminated aggregates. Chlorides that penetrate concrete can come from contact with seawater or sea salt spray, deicing salts, and various chemicals. The degree of chloride contamination of concrete that will activate the corrosion process. The main factor influencing the ability of concrete to resist chloride contamination is adequate cover of reinforcing steel by sand, crack-free, impermeable concrete. Chlorides- induced corrosion is very common for highway structures exposed to seawater or deicing salts. Long before carbonation becomes a problem for these structures, chlorides cause corrosion.

2.3 Corrosion process in seawater

Electrochemically, corrosion of steel in natural water can be represented as an iron electrode in a dilute aerated neutral or basic electrolyte. [2] Unprotected, steel corrodes in seawater per the anodic reaction:

$$Fe -> Fe^{+2} + 2e^- \qquad (2.3.1)$$

The corresponding cathodic reaction is:

$$O_2 + 2H_2O + 4e^- -> 4OH^- \qquad (2.3.2)$$

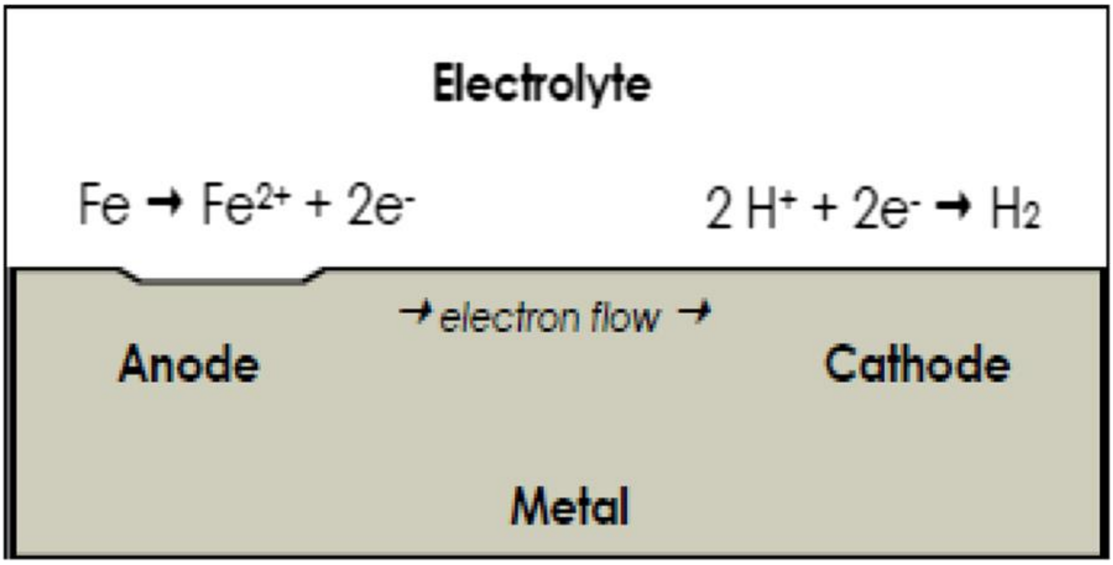

Figure 2.1: Corrosion Process

As shown in the above equations, anodic and cathodic reactions are the first step in corrosion because the OH^- will react with ferrous iron (Fe^{+2}), as shown in equation 2.3.3. This reaction produces ferrous hydroxide, which will react, as shown in equation 2.3.4, with oxygen and water and produce ferric hydroxide, $Fe(OH)_3$, and the last component, which is the hydrate ferric oxide (rust). The chemical term for rust, Fe_20_3-H_2O, is shown in equation 2.3.5. [20]

$$Fe^{+2} + 2OH^{-} -> Fe(OH)_2 \quad (2.3.3)$$

$$4Fe(OH)_2 + O_2 + 2H_2O -> 4Fe(OH)_3 \quad (2.3.4)$$

$$2Fe(OH)_3 -> Fe_2O_3 - H_2O + 2H_2O \quad (2.3.5)$$

Corrosion (Figure 2.1) is a major problem in offshore environments due to extreme operating environments and the presence of aggressive corrosive elements. In a wide range of offshore applications seen in the Oil and Gas market, resistance to corrosion can represent the difference between trouble-free long-term operation and costly downtime. With the presence of extreme corrosive elements such as hydrogen sulphide, carbon dioxide, brine and a whole range of hazardous chemicals compounded by extreme temperatures and pressures, there are few more arduous environments than offshore.

Steel is subject to a variety of corrosion phenomena: atmospheric corrosion, splash zone corrosion, crevice corrosion, etc. Recently, many steel structures in service in seawater have been corroded by microorganisms spawned by the interaction of aerobic and anaerobic bacteria. Steel structures, such as oil platforms and pipelines, left unprotected in these aggressive environments, will ultimately fail due to inadequate corrosion control. This, in turn, leads to loss of productivity, loss of life, and pollution.

2.4 Corrosion problems in oil and gas industry

In the oil and gas industry, carbon dioxide (CO_2) and hydrogen sulfide (H_2S) are commonly present, and water is their catalyst for corrosion. When water combines with CO_2 and H_2S, the environments form the following reactions:

$$H_2CO_3\ Reaction: Fe + H_2CO_3 -> FeCO_3 + H_2 \quad (2.4.1)$$

$$H_2S\ Reaction: Fe + H_2S + H_2O -> FeS + 2H \quad (2.4.2)$$

There may be a combination of the above two reactions if both gases are present. These resulting molecules either attach themselves to the cathode or are released into the electrolyte and the corrosion process continues.

2.4.1 Types of corrosion in oil and gas industry

It is a great challenge to classify the types of corrosion in the oil and gas industry in a uniform way. One can divide the corrosion on the basis of appearance of corrosion damage, mechanism of attack, industry section, and preventive methods. There are many types and causes of corrosion. The mechanism present in a given piping system varies according to the fluid composition, service location, geometry, temperature, and so forth. In all cases of corrosion, the electrolyte must be present for the reaction to occur. In the oil and gas production industries, the major forms of corrosion include sweet corrosion, sour corrosion, oxygen corrosion, galvanic corrosion, crevice corrosion, erosion corrosion, microbiologically induced corrosion, and stress corrosion cracking.

1. Sweet corrosion (CO_2 corrosion) – CO_2 corrosion has been a recognized problem in oil and gas production and transportation facilities for many years. CO_2 is one of the main corroding agents in the oil and gas production systems. Dry CO_2 gas is not itself corrosive at the temperatures encountered within oil and gas production systems but is so dissolved in an aqueous phase through which it can promote an electrochemical reaction between steel and the contacting aqueous phase.
   CO_2 will mix with the water, forming carbonic acid making the fluid acidic. CO_2 corrosion is influenced by temperature, increase in pH value, composition of the aqueous stream, presence of non-aqueous phases, flow condition, and metal characteristics and is by far the most prevalent form of attack encountered in oil and gas production. At elevated temperatures, iron carbide scale is formed on the oil and gas pipe as a protective scale, and the metal starts to corrode under these conditions.

2. Uniform corrosion – sees a decrease in metal thickness per unit of time or uniform deposit of corrosion products on the surface of the metal (sometimes also known as general corrosion).

3. Galvanic corrosion – results from contact between two different materials in a conducting, corrosive environment. Galvanic corrosion may result in the very rapid deterioration of the least resistant of the two materials leading to a fatal failure. Avoiding the mixing of different materials, for example on tubes and fittings or valves, is the most common method of minimising the problem.

4. Crevice corrosion – is an electromechanical oxidation reduction process. It occurs within localised volumes of stagnant trapped solution trapped in pockets, corners or beneath a shield of some description. The corrosive process is greatly

accelerated if chlorine, sulphide or bromide ions are present in the electrolyte solution. Crevice corrosion is considered far more dangerous than uniform corrosion as the rate at which it acts can be up to 100 times higher.

5. Pitting corrosion – is characterised by deep, narrow holes that can penetrate inwards extremely rapidly while the remainder of the surface stays intact. Perforation of a component can occur in a few days with no appreciable reduction in weight of the overall structure. Stainless steels are particularly sensitive to pitting corrosion in seawater environments.

6. Intergranular corrosion – progresses along the grain boundaries of an alloy and can result in the catastrophic failure of equipment, especially if tensile stress loads are present. Localised attack can occur while the rest of the material is completely unaffected. The presence of impurities in the boundaries or local enrichment or depletion of one or more alloying elements can be the catalyst for this type of corrosion.

7. Stress corrosion cracking – sees a combination of tensile loading and a corrosive medium causing the initiation of cracks and then their growth. Time to failure depends on specific application factors and can vary from just a few minutes to several years. Stress corrosion cracking is a very serious and permanent risk in many industrial applications where materials are often under mechanical loading for sustained periods or indeed permanently. In addition to selecting the correct materials, the risk of this type of corrosion can be avoided by stress relieving or annealing after fabrication of the assembly, avoiding surface machining stresses and controlling the corrosive environment.

2.5 Problem areas in offshore structures

The corrosion problems for steel structures in seawater have been well studied over many years, but despite published information on materials behavior in seawater, failures still occur.

The offshore structures are installed in the sea water. So, some of the structure is submerged, and some part of it is above the water level, exposed to atmospheric elements; however, there will be some parts of the structure that are in a zone where they are intermittently in and out of seawater, primarily due to shifting water levels resulting from tidal movement. These three areas of varying exposure are called zones and they are:

1. Atmospheric zone
2. Splash zone
3. Submerged zone

2.5.1 Atmospheric zone

The atmospheric zone refers to the section of the structure which is solely exposed to air. In other words, it is not affected by the change in tidal waves and therefore remains mostly dry and is not in constant exposure to an electrolyte. The unmitigated corrosion rate of carbon steel in a marine atmospheric zone is in the range 0.1 to 0.3 mm/yr at ambient temperature. [24]

2.5.2 Splash zone

The splash zone is the section of the structure that is intermittently in or out of seawater during the structure's service life. This is exposed to regular soaking by the waves and spray, being partially dried out by the salt-laden air. These are ideal conditions for the promotion of corrosion.

The range of the zone varies with the height of the sea's rise and fall due to daily tide cycles in the specific geographic area. For example, the range of the splash zone in the Gulf of Mexico is about 6 ft., but it is about 33 ft. in North Sea and about 1m (3.32 ft.) in the North China Sea. Extremely corrosive conditions may prevail for hot risers just above the water level; 3-10 mm/yr has been reported for risers with a wall temperature of about 100°C. [24] In the splash zone below the water level, the unmitigated corrosion rate is close to that in the seawater submerged zone (see 2.5.3).

2.5.3 Seawater Submerged zone

The submerged zone is the section of the structure that is below the lowest end of the splash zone and is always below the sea level. The corrosivity of the seawater submerged zone is relatively low and unmitigated carbon-steel corrosion rates in excess of 0.1 mm/yr would only be expected for surfaces heated by an internal fluid. For ambient temperature surfaces, the unmitigated corrosion rate is below 0.1 mm/yr. [24]

The image below (Figure 2.2) shows severe corrosion of an offshore tower support structure close to the splash zone.

Figure 2.2: Corrosion of an offshore tower support structure

2.6 Investment in materials research

Aside from the obvious issues such as the need to shutdown plant or equipment to repair, replace or carry out preventative maintenance on corroded items, there are also issues that include expensive overdesign to compensate for anticipated corrosion, decreases in system efficiency and related failures of adjacent equipment to consider and contend with.

In most cases properly analyzing the specific operating parameters and defining the correct material for use through the collaborative efforts of the customer and the supplier of the components or systems can ensure these situations are avoided.

Leading industrial engineering companies, such as Parker, are continually committing heavy investment into materials research and development to deliver offshore products that meet the increasingly demanding application challenges in the sector.

As an example of the potential impact of poor material selection leading to corrosion, in the USA, it was reported that the cost of corrosion accounted for an astonishing $276 billion per year. This total loss included the values from a number of sectors, including utilities, transportation, production and manufacturing and infrastructure.

2.7 Material selection for oil and gas applications

The types of materials used in components for offshore use by companies, such as Parker, include 6Mo, Super Duplex, Monel, Hastelloy, Titanium & Alloys 825 and 625. These are utilised within items such as fittings, valves, manifolds and flanged products. Whilst these materials can be more expensive than less corrosion resistance alternatives, it is important for offshore equipment specifiers to factor in the massive potential cost savings associated with medium and long-term trouble-free operation.

As an example, in a comparison of low initial material cost stainless steel 316 tubing and fittings versus highly corrosion resistant Superaustenitic 6Mo equivalents, it was found that after factoring labour and maintenance costs needed over a 10-year period, using the corrosion resistant parts gave a total cost of ownership saving in the region of 40%. In addition to finished parts and expertise about environmental conditions that affect material selection, it is also important for suppliers of components for offshore applications to give advice about other factors. These include compliance with legislation and internal regulations that have increasing importance in the field of oil and gas offshore exploration and production.

3 CORROSION CONTROL OF OFFSHORE STRUCTURES

Chapter three refers to different corrosion control methodologies, coatings and cathodic protection. It describes the most effective coatings for offshore structures and the advantages of the application of cathodic protection.

3.1 General

For steel in seawater, corrosion control is based on maintaining a potential equal to or more negative than -0.80 $^{VAg}/_{Agci}$ to achieve adequate corrosion protection and also more positive than -1.05 $^{VAg}/_{Agci}$ to avoid overprotection and hence the risk of hydrogen evolution [10].

Protecting against corrosion on offshore structures generally comes down to preventing the oxidation of steel in the humid, salt laden environment that exists offshore. In terms of corrosion protection, platform designers in the Gulf of Mexico divide a structure into three distinct regions: underwater (immersed zone), waterline or splash zone (± 10 feet from MLW) and topsides (+10 feet and above).

3.2 Corrosion control at three zones

In the atmospheric zone, the corrosion control is achieved through the application of a suitable coating system. Given that this zone is not in contact with the electrolyte (seawater), the coating does not need to be complimented by cathodic protection.

In the splash zone, just above and below the water line, good corrosion prevention practice is the application of a Cathodic Protection system. In this zone a part of the structure is intermittently in and out of seawater during the structure's service life and this is why the corrosion control in this zone is the most difficult to be achieved than the 3 others zones. While the part of the structure is moving in and out the seawater the cathodic protection current fluctuates tremendously. More specifically, the effect of sacrificial anode reduces while the part of the structure is drying out. Sacrificial anode cannot work properly in the area of splashed zone and the reason is that there are no stable electrolytes around the metalwork to enable the anode to function. [22] Figure 3.1 below shows the morphology of bare surfaced rod after one year's exposure at splash zone, left is the upper half without removal of rust; right is the lower half, with rust removed. The severity of corrosion in splash zone is clearly shown. The corrosion rate of bare surfaced rod is 0.2920 mm/yr.

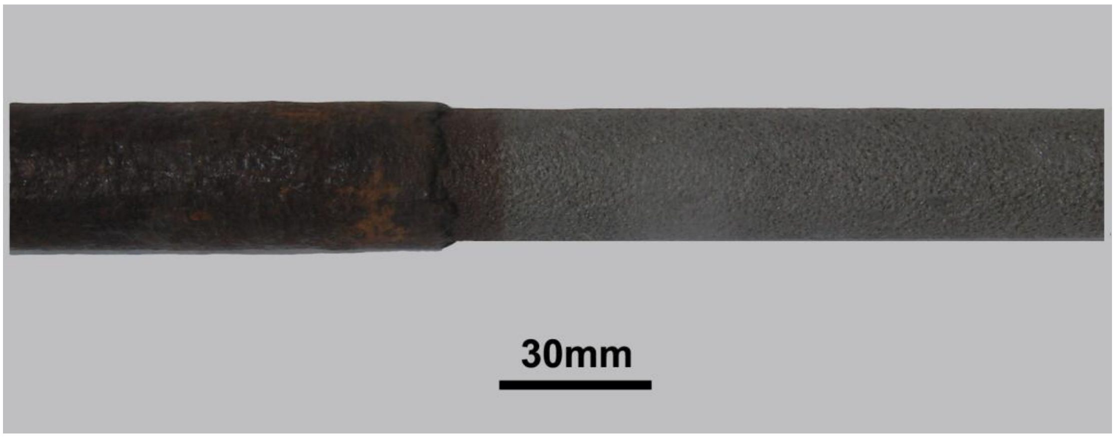

Figure 3.1: Morphology of bare surfaced rod after one year’s exposure at splash zone, left is the upper half without removal of rust; right is the lower half, with rust removed.

It is important to select a suitable material that can be applied to the splash zone to form a stable electrolyte layer. Four kinds of fabrics cotton, linen, dacron and chemical fiber are used for seawater absorption to enable sacrificial anode’s function of cathodic protection at splash zone. It has been noticed that linen is the best among the four kinds of fabrics and it has the best seawater absorbing capacity. When the part of the structure is wrapped with one layer of linen the fluctuation of current is greatly reduced because linen has the ability of preserving seawater when the part of the structure is moving out the seawater. The sacrificial anode still function as a result of continuous electrolyte layer forming around the part of the structure. Figure 3.2 shows the morphology of a rod enlaced with pure zinc wire and wrapped with a layer of linen after one year’s exposure at splash zone. The corrosion rate of sacrificial anode protected rod is 0.00375 mm/a. [22] The protection efficiency by sacrificial anode in marine splash zone is 98.7%.

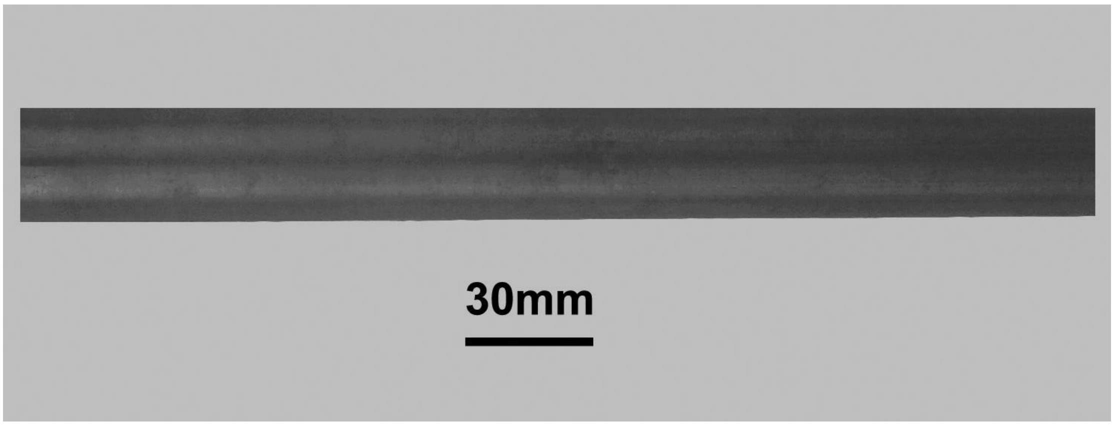

Figure 3.2: Morphology of a rod enlaced with pure zinc wire and wrapped with a layer of linen after one year’s exposure at splash zone.

In the underwater or immersed zone, good practice is characterized by the use of anode based cathodic protection systems which, when properly designed and maintained, inhibits corrosion extremely well. The integrity of these systems is annual checked by monitored the anode driven potential between the platform steel and the surrounding saltwater. From the cathodic protection point of view, this portion of the structure is always in the electrolyte.

3.3 Coatings

The conventional approach to the prevention of external corrosion is to cover the exposed surfaces with a high-efficiency coating, while making the structure a cathode in relation to an anode placed in the electrolyte formed by seawater.

3.3.1 Standards for coatings

NACE TG260
– “Offshore Platform Atmospheric and Splash zone Maintenance Coatings”
NACE TG263
– “Offshore Platform Ballast Water Coatings”
– New Construction and Maintenance
NACE TG264
– “Offshore Platform Exterior Submerged Coatings”

DNV rules require that the provisions for coating include:

1. A description of general application conditions at coating yard
2. Method and equipment for surface preparation
3. Ranges of temperature and relative humidity
4. Application methods
5. Time between surface preparation and first coat
6. Minimum and maximum dry film thickness of a single coat
7. Number of coats and minimum total dry film thickness
8. Relevant drying characteristics
9. Procedure for repair of damaged coating
10. Methods of inspection – for example, adhesion testing and holiday detection.

3.3.2 Benefits from the application of coatings

Typical rates of corrosion of uncoated steel in seawater are 0.15 $^{mm}/_{year}$ in the splash zone, 0.07 $^{mm}/_{year}$ in the submerged zone, except more, up to 0.03 $^{mm}/_{year}$, in cold fast running tides carrying silt or other abrasive sediments. [15] Other studies for uncoated steel in seawater give rates of 0.127 $^{mm}/_{year}$. Rates in fresh water are about half of those in seawater.

Painting and coating of steel members, where specified, should be carried out as far as practicable in the shop, under appropriate conditions of humidity and protection from extremes of weather. The joint surfaces should, of course, be masked to permit welding. Field coating of the joints and touchup of shop coats should be done only when the surfaces are dry and at the proper temperature. In some locations, portable tents or other protection will have to be provided. Heaters and/or dehumidifiers may be required.

Generally, coatings may delay initiation of corrosion by 10-20 years. Coatings are usually applied to steel in the splash and atmospheric zones and to internal spaces that are corrosion inhibitors may be added to the water prior to sealing.

The most effective coatings seem to be organic coatings over metallized zinc: vinyl mastic on urethane in temperate zones over zinc or zinc silicate and phenolic over the zinc primer in arctic and subarctic. [9]

Reinforcing steel is protected against corrosion by the semi-impermeability of concrete cover and by its alkalinity. Carbon dioxide from the air and chlorides from seawater or intentionally applied salts degrade this protective encasement. Corrosion is especially severe in the splash zone but can extend up well into the atmospheric zone where spray periodically deposits salt by evaporation, which then becomes concentrated.

3.3.3 Coating Selection Criteria for Offshore Service

There are two categories of selection criteria for offshore service, namely the obligatory criteria and the desirable criteria.

3.3.3.1 Obligatory Criteria

The obligatory criteria listed below are considered the major factors affecting coating performance.

1. Resistant to service environment
2. Meets applicable regulatory requirements
3. Compatible with substrate and surface preparation
4. Compatible with available application techniques
5. Compatible with cathodic protection

3.3.3.2 Desirable Criteria

The desirable criteria listed below may be considered necessary to project success:

1. Costs required to achieve effective protection
2. Low first cost
3. Low life-cycle cost
4. Duration of effective protection
5. Others

3.3.4 Causes of Coating Failures

Coatings fail for a number of reasons, but by far, the principal reasons for coating failure are deficient surface preparation and insufficient coating thickness. [14] However, these application related failures are readily observable and/or detectable at the time of surface preparation and coating application. With a conscientious paint contractor, and good independent inspection, surface preparation and coating thickness deficiencies can be readily corrected.

3.3.5 Cost of coatings

When looking at the cost of a coating system, one must consider performance. Comparisons must be normalized on an equal basis. [9] Generic type of coating, solids content and various other properties must be compared. Again, cost is less important than performance in most instances.

3.4 Cathodic protection

Cathodic protection (CP) is primarily intended for metal surfaces permanently exposed to seawater or marine sediments. Still, CP is often fully effective in preventing any severe corrosion in a tidal zone and has a corrosion reducing effect on surfaces intermittently wetted by seawater. CP can be defined as e.g. “electrochemical protection by decreasing the corrosion potential to a level at which the corrosion rate of the metal is significantly reduced” (ISO 8044) or “a technique to reduce corrosion of a metal surface by making that surface the cathode of an electrochemical cell” (NACE RP0176). [19]

3.4.1 Methods of cathodic protection

There are two types of cathodic protection:

1. Protection with an external source of direct electrical current (ICCP)
2. Passive protection with active anode – Sacrificial Anode

The main difference between the two is that ICCP uses an external power source with inert anodes and SACP uses the naturally occurring electrochemical potential difference between different metallic elements to provide protection.

3.5 Cathodic protection combined with coatings

Combining Cathodic Protection (CP) with a protective coating is generally believed to be the best method for protecting submerged structures. [14] Sykes, at the 1999 New Orleans Offshore Corrosion Conference, demonstrated that the corrosion rate of an unprotected insulated twelve-inch tubular member exhibited 14 mils per year (mpy) corrosion rate versus less than two mpy for a member attached to the offshore structure and cathodically protected (Figure 3.3).

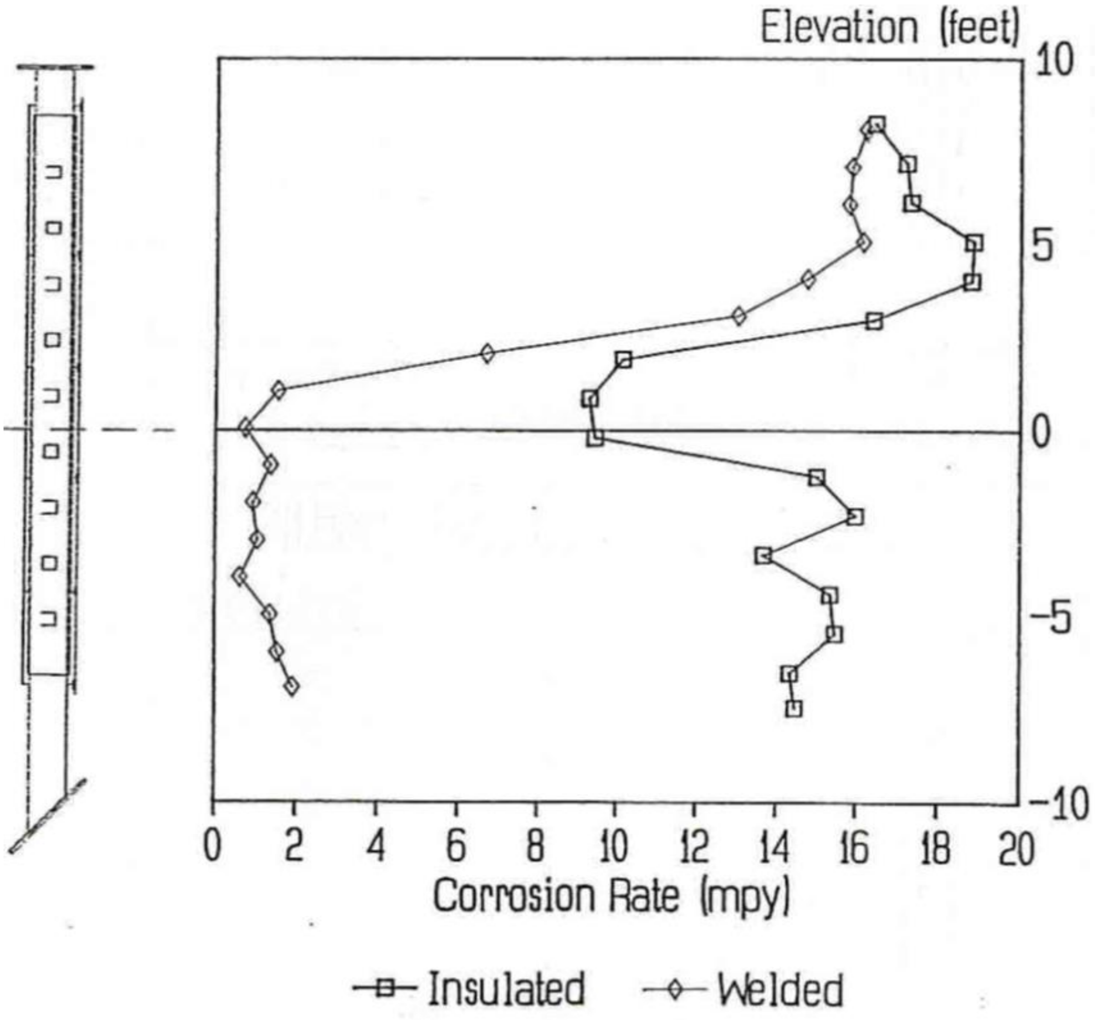

Figure 3.3: Corrosion rate as a function of elevation of 12 inch tubular members electrically coupled to offshore platform structure

CP system design and coating selection must be compatible if the structure is to reach and possibly exceed its design life. [13] Compatibility can be achieved through effective communications between coating selectors and CP system designers. Robust CP system designs can offset less than optimal coating selections and vice-versa. However, too robust a CP system may cause cathodic disbandment and other problems with an otherwise suitable coating system. Thick coatings for thermal insulation may hinder (shield) effective CP of critical surfaces.

3.6 Advantages and uses of cathodic protection

The main advantage of cathodic protection over other forms of anti-corrosion treatment is that it is applied simply by maintaining a dc circuit and its effectiveness may be monitored continuously. [21] Cathodic protection is commonly applied to a coated structure to provide corrosion control to areas where the coating may be damaged. It may be applied to existing structures to prolong their life.

Cathodic protection can, in principle, be applied to any metallic structure in contact with a bulk electrolyte (including concrete). In practice, its main use is to protect steel structures buried in soil or immersed in water. It cannot be used to prevent atmospheric corrosion on metals. However, it can be used to protect atmospherically exposed and buried reinforced concrete from corrosion, as the concrete itself contains sufficient moisture to act as the electrolyte.

Structures that are commonly protected by cathodic protection are the exterior surfaces of:

1. Pipelines
2. Ships' hulls
3. Storage tank bases
4. Jetties and harbour structures
5. Steel sheet, tubular and foundation pilings
6. Offshore platforms, floating and subsea structures

Cathodic protection is also used to protect the internal surfaces of:

1. Large diameter pipelines
2. Ship's tanks (product and ballast)
3. Storage tanks (oil and water)
4. Water-circulating systems.

3.7 Duration of corrosion protection

The length of time that a properly selected and applied coating will provide protection from significant corrosion depends on the rate of degradation of the coating in the particular service environment. [14] Subjective evaluations of degradation rate are suitable for small projects or projects with low risk, i.e., low consequences of failure. However, when projects with higher levels of risk require a more objective approach such as that provided by a combination of laboratory and field-testing is needed costs may be higher.

3.8 Costs of protection

The cost of effective corrosion protection by protective coatings can come from a number of cost drivers. Cost of materials (paint and abrasives); labor costs for surface preparation and application, equipment and access costs (scaffolding, rigging) are the major items. Transportation costs in an offshore environment can also be a high-ticket item.

The wrong choice of material for an application can, as a minimum, lead to increased downtime, unscheduled maintenance and lost production, and at worst to catastrophic failure and potential human, environmental and economic loss. There are a wide range of potential direct, and sometimes overlooked, indirect costs associated with corrosion.

As mentioned previously, the best result for corrosion control is the combination of Cathodic Protection systems with coatings. Figure 3.4 presents the cost comparison between the submerged steel without any CP (Cathodic Protection) technique, with SACP (Sacrifiacial Anode Cathodic Protection), and with ICCP (Impressed Current Cathodic Protection). As expected, applying no CP system results in the highest cost to the vessel in question (nearly 46,000 USD after 20 years). On the other hand, CP and corrosion repairs cost 10,000 USD to a ship with ICCP after 20 years in service. This amount reaches 25,000 USD for a vessel with SACP after the same length of time in service. It should be concluded that the cost after 20 years with sacrificial anodes is circa 2.5 times higher than the vessel with ICCP. [23]

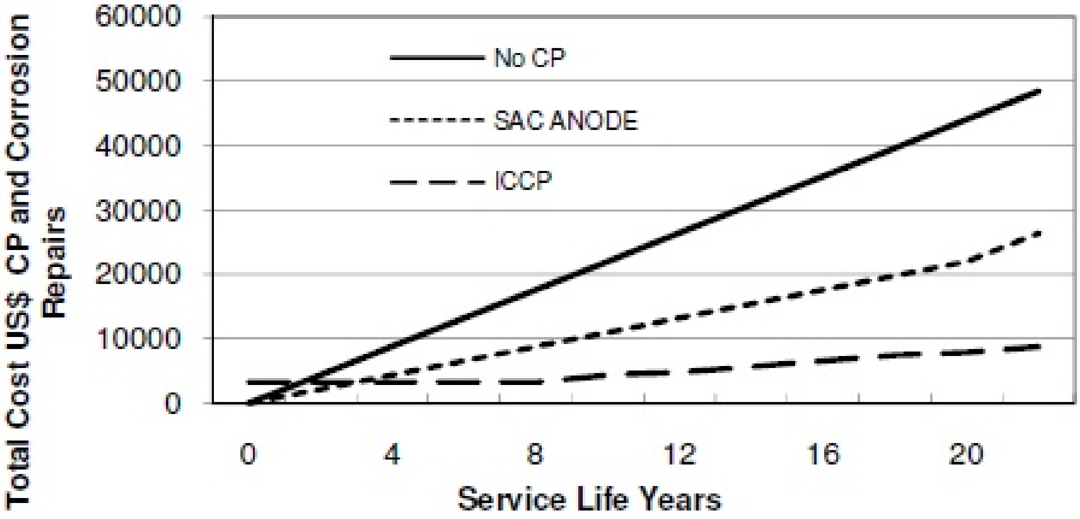

Figure 3.4: Cost comparison of Cathodic Protection systems (per 100 m² of underwater steel)

4 CATHODIC PROTECTION

In this chapter, the method of cathodic protection which is used for corrosion control of offshore structures is described in depth. In addition, the principles of the method and its application are analyzed. The two different methods of cathodic protection, namely the ICCP (Impressed Current Cathodic Protection) and the Sacrificial Anode Cathodic Protection are presented and the materials of the anodes for each method of Cathodic Protection are mentioned.

4.1 Introduction

The first practical use of cathodic protection is generally credited to Sir Humphrey Davy in the 1820s. Davy's advice was sought by the Royal Navy in investigating the corrosion of copper sheeting used for cladding the hulls of naval vessels. Davy found that he could preserve copper in sea water by the attachment of small quantities of iron or zinc; the copper became, as Davy put it, "cathodically protected".

The most rapid development of cathodic protection systems was made in the United States of America to meet the requirements of the rapidly expanding oil and natural gas industry which wanted to benefit from the advantages of using thin-walled steel pipes for underground transmission. For that purpose, the method was well established in the United States in 1945.

4.2 Application of cathodic protection method

Cathodic protection can, in principle, be applied to any metallic structure in contact with a bulk electrolyte. [5] It is commonly used to protect steel, water or fuel pipelines and storage tanks, steel pier piles, water-based vessels including yachts and powerboats, offshore oil platforms and onshore oil well casings. [3]

Cathodic Protection is one of the most effective and well-known methods of corrosion control for marine structures. Cathodic protection has also been applied to steel embedded in concrete, to copper-based alloys in water systems, and, exceptionally, to lead-sheathed cables and to aluminium alloys, where cathodic potentials have to be very carefully controlled. [5] It can prevent or reduce the corrosion of any metal or alloy exposed to an aggressive environment. Cathodic protection extends the service life of thousands of miles of buried steel pipelines, offshore oil drilling structures, seagoing ship hulls, water tanks, and some chemical equipment. [4]

4.3 Principles of this method

Cathodic protection systems polarize the cathode by delivering an excess of electrons and thereby reducing the rate of the anodic reaction. The rationale behind cathodic protection is to prevent the reinforcing steel from giving up electrons so that corrosion does not occur.

Anodic reactions involve oxidation of metal to its ions occurs. Consider the corrosion half–cell reactions introduced in Section 2.3 (equation 2.3.1). Hereinafter, this reaction will be referred to as anodic reaction (1).

The cathodic process involves reduction and several reactions are possible. In acidic water, where hydrogen ions (H+) are plentiful, the following reaction occurs.

$$2H^{+} + 2e^{-} -> H_2 \qquad (4.3.1)$$

Hereinafter this reaction will be referred to as cathodic reaction (2).

In alkaline solutions, where hydrogen ions are rare, the reduction of water will occur to yield alkali and hydrogen.

$$2H_2O + 2e -> H_2 + 2OH^{-} \qquad (4.3.2)$$

However, unless the water is deaerated, reduction of oxygen is the most likely process, again producing alkali at the surface of the metal (equation 2.3.2).

Anodic reaction (1) and cathodic reaction (2) are shown schematically in Figure 4.1, where anodic and cathodic sites are nearby on the surface of a piece of metal. We can change the rate of these two reactions by withdrawing electrons or supplying additional electrons to the piece of metal. It is an established principle that if a change occurs in one of the factors under which a system is in equilibrium, the system will tend to adjust itself so as to annul, as far as possible, the effect of that change.

Thus, if we withdraw electrons from the piece of metal the rate of anodic reaction (1) will increase to attempt to offset our action and the dissolution of iron will increase, whereas cathodic reaction (2) will decrease. Conversely, if we supply additional electrons from an external source to the piece of metal, anodic reaction (1) will decrease to give reduced corrosion and cathodic reaction (2) will increase. The latter case will apply to cathodic protection. Thus, to prevent corrosion we have to continue to supply electrons to the steel from an external source to satisfy the requirements of the cathodic reaction. Note that the anodic and cathodic processes are inseparable. Reducing the rate of the anodic process will allow the rate of the cathodic process to increase.

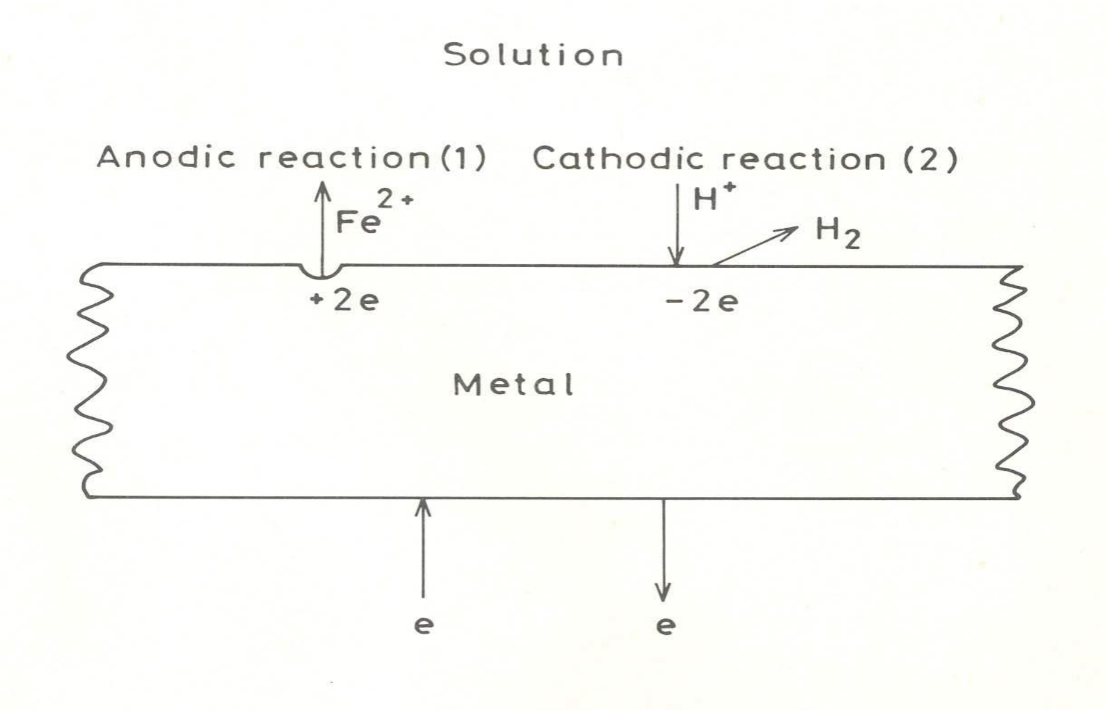

Figure 4.1*:***Anodic and cathodic reactions at a metal surface**

These principles may be expressed in a more quantitative manner by plotting the potential of the metal against the logarithm of the anodic and cathodic reaction rates expressed as current densities. Typical anodic and cathodic curves are illustrated in Figure 4.1. The corrosion current, Icorr, and the corrosion potential, Ecorr, occur at the point of intersection of the anodic and cathodic curves, i.e. where anodic and cathodic reactions rates are equal. If electrons are "pumped" into the metal to make it more negative the anodic dissolution of iron is decreased to a negligible rate at a potential E_1, whereas the rate of the cathodic current is increased to I_1.

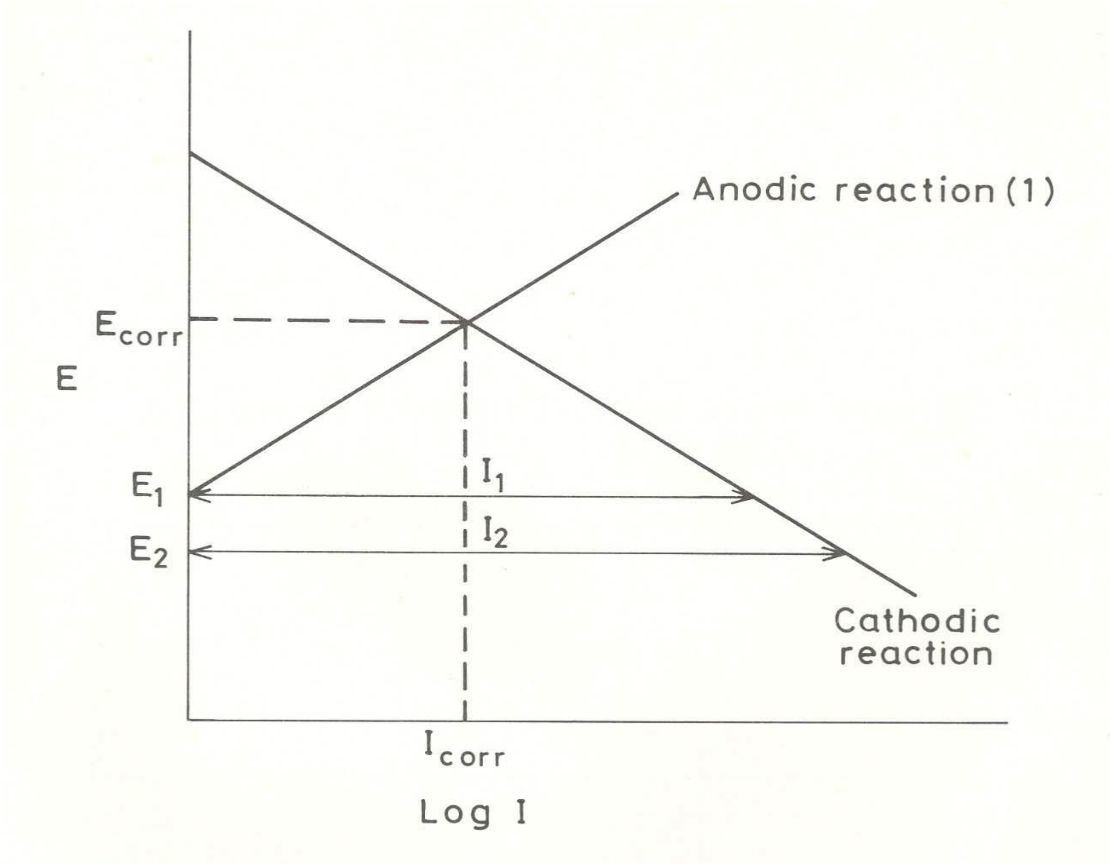

Figure 4.2: Kinetics of anodic and cathodic reactions

Hence, a current I_1 must be supplied from an external source to maintain the potential at E_1 where the rate of dissolution of the iron is at a low value. If the potential is reduced to E_2 (Figure 4.2) the current required from the external source will increase to I_2. Further protection of the metal is insignificant, however, and the larger current supplied from the external source is wasted. The metal is then said to be over-protected.

In aerated neutral or alkaline solutions, the cathodic corrosion process is usually the reduction of oxygen. The kinetics of this cathodic process are controlled by the rate at which oxygen can diffuse to the surface of the metal, which is slower than the rate of consumption of oxygen by the cathodic reaction. Thus, the rate of this reaction does not increase as the potential of the metal is made more negative but remains constant unless the rate of supply of oxygen to the surface of the metal is increased by, for example, increase fluid flow rate. The influence of flow velocity on cathodic protection parameters is illustrated in Figure 4.3. A current of I_1 is initially required to maintain the metal at the protection potential E_1. However, if the flow rate is increased the limiting current for the reduction of oxygen is increased (dotted line) and the current required to maintain the metal at the protection potential is increased by ΔI. Thus, the current density required to maintain the correct protection potential will vary with service conditions. Clearly, cathodic current density is not a good guide as to whether a structure is cathodically protected. The correct protection potential must be maintained if corrosion is to be prevented.

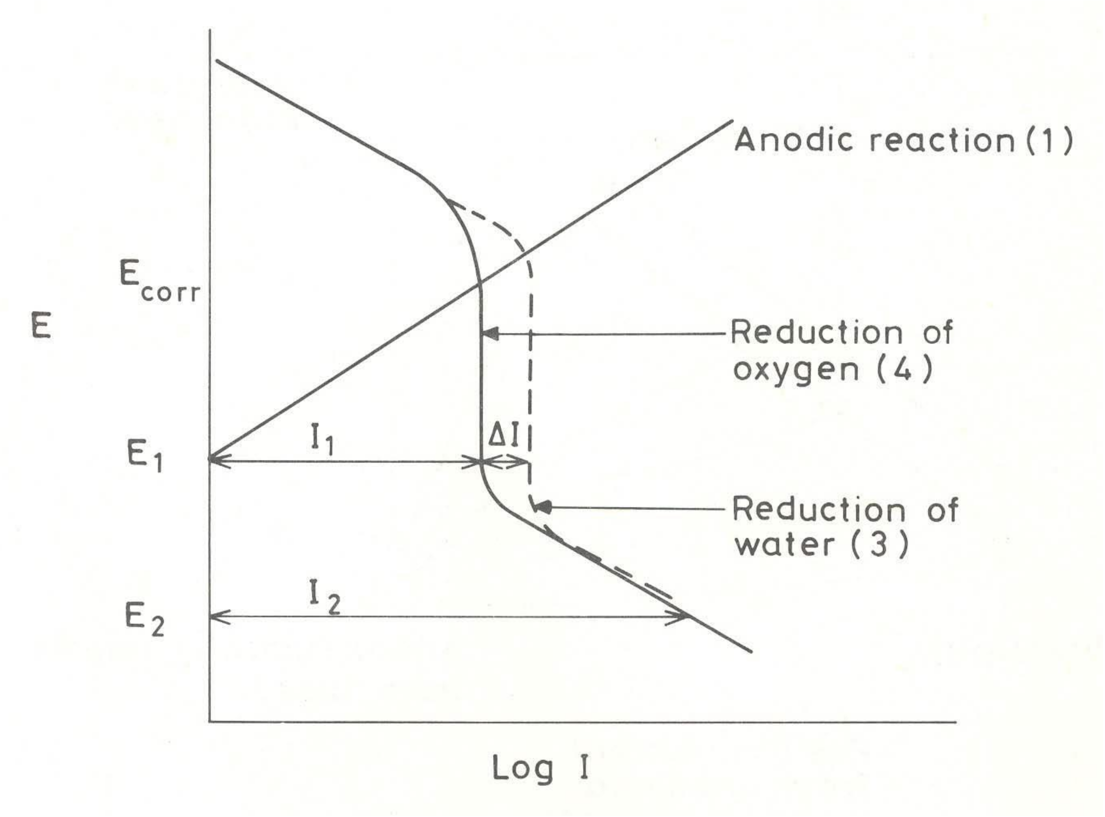

Figure 4.3: Diffusions controlled reduction of oxygen

If the structure is over-protected and the potential is reduced to a potential region where reduction of water (reaction 3) can take place, further current will be required from the external source and current will be wasted. In Figure 4.3 reducing the potential from E1 to E_2 will increase the current required from the external source from I_1 to I_2 as a result of an increased rate of reduction of water.

Excessive negative potentials can cause accelerated corrosion of lead and aluminum because of the alkaline environments created at the cathode. [16] These alkaline conditions may also be detrimental to certain paint systems, and may cause loss of the paint film. Hydrogen evolution at the cathode surface may, on high-strength steels, result in hydrogen embrittlement of the steel, with subsequent loss of strength. It may also cause disbanding of any insulating coating: the coating would then act as an insulating shield to the cathodic protection currents.

4.4 Description of cathodic protection methods

4.4.1 Impressed Current Cathodic Protection (ICCP)

Impressed current cathodic protection (ICCP) systems are used throughout the world to provide cathodic protection for pipelines, ship hulls, offshore production platforms, water and wastewater treatment equipment, tank farms, and of course, underground storage tank systems. [17]

The Impressed Current Cathodic Protection system comprises of several anodes, reference electrodes and a transformer/rectifier controller power unit. The types and sizes of these components and their positions are specified according to design parameters. (Figure 4.4).

This type of Cathodic Protection relies on an external direct current source to be forced into the water from an inert non-wasting anode. The electrical power is taken from the main AC power, through the transformer/rectifier controller power unit, providing a low voltage DC output to the anodes. [19] Examples of power sources are transformer rectifier units, solar generating units, or thermoelectric generators. [12]

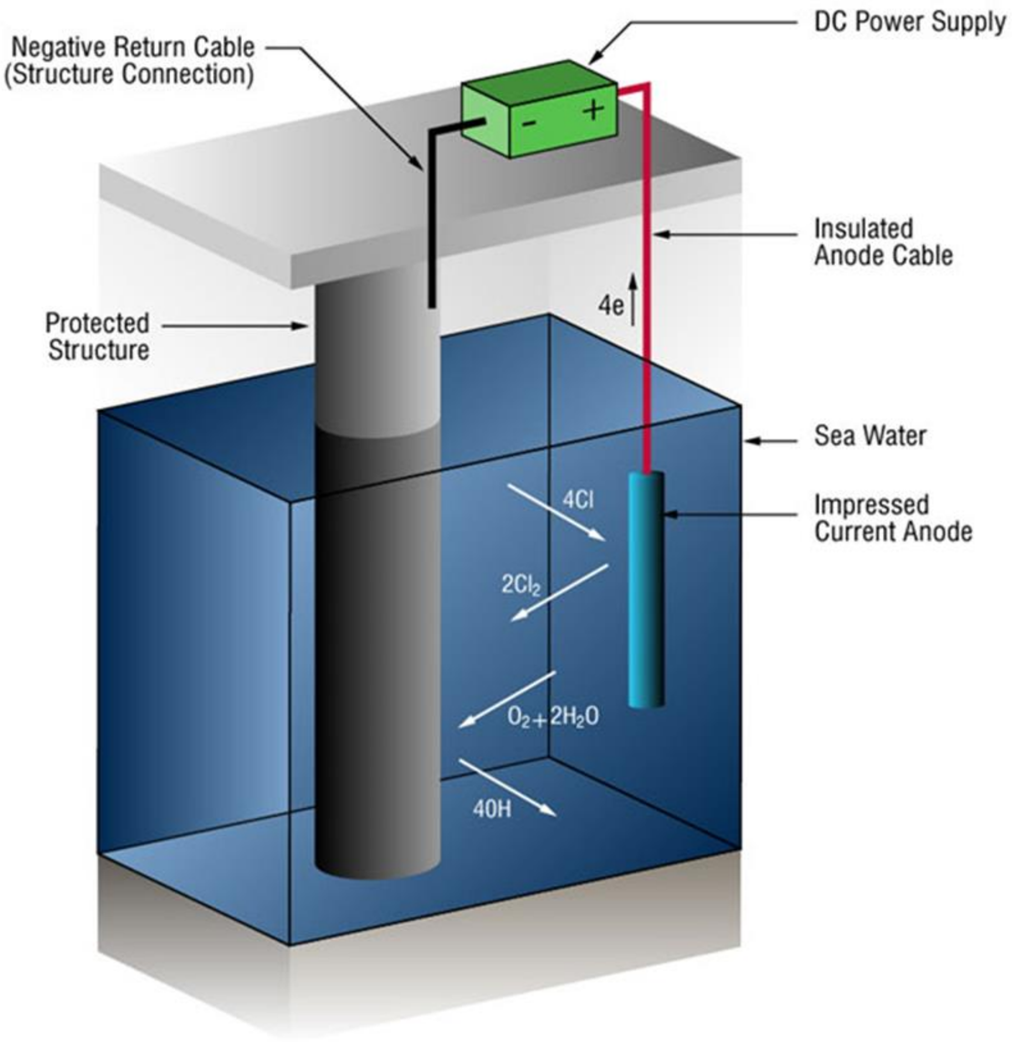

Figure 4.4: Impressed-current cathodic-protection system in seawater

The structure becomes the cathode and the auxiliary electrode the anode. The auxiliary electrode sometimes consists of scrap iron. In this case, the iron will dissolve from the anode by anodic reaction (1) and the electrode is described as a consumable anode. If the anode is a noble metal or an electrochemically inert material, the surrounding environment will be oxidized and in water reaction (reaction below) will occur. In saline solutions, however, chlorine may be produced at the anode. This may present problems in confined spaces.

$$2H_2O -> \ O_2 + 4H^+ + \ 4e^- \qquad (4.4.1)$$

Due to the high currents involved in many seawater systems, it is not uncommon to use impressed-current systems that use anodes of a type (ICCP anodes) that are not easily dissolved into metallic ions. This causes an alternative reaction: the oxidization of the dissolved chloride ions (reaction below).

$$2Cl^{-} -> Cl_2 + 2e^{-} \qquad (4.4.2)$$

4.4.1.1. Anodes for Impressed Current Systems

The impressed current anodes are either inert or have low consumption rates and can be surrounded by carbonaceous backfill to increase efficiency and decrease costs. Typical anodes are titanium coated with mixed metal oxide or platinum, silicon iron, graphite, and magnetite. [12]

There are many different anode materials available for use and most are capable of providing 100 to 10,000 times the amount of current provided by a galvanic anode. [17]

A range of materials have been used as non-consumable anodes for impressed-current systems. The sort of properties required by these anodes are:

1. good electrical conduction,
2. low rate of corrosion,
3. good mechanical properties, able to stand the stresses which they may be subjected to during installation and in service,
4. readily fabricated into a variety of shapes,
5. low cost,
6. able to withstand high current densities at their surfaces without forming resistive barrier oxide layers, etc.

Graphite and high silicon cast iron are the most commonly used impressed current cathodic protection anode materials, however, other materials (such as magnetite, platinum, and newly developed ceramic materials) have been successfully used.

4.4.2 Sacrificial Anode Cathodic Protection

The principle for cathodic protection using sacrificial anodes is quite simple: the steel structure is electronically connected to a less noble metal, for example aluminum, which causes the sacrificial anode to be anodically polarized and the steel structure to be cathodically polarized when the electrodes are immersed in seawater. This system relies upon the natural potential difference between the structure (pipe or platform) and the anodes [2]. The sacrificial anode, also called galvanic anode, is the current source for the CP system and will be consumed, as corrodes preferentially producing electrons. [18]

Electrons are supplied to the steel pipe, via the electrical connection, and a corresponding amount of anode material goes into solution as metal ions, according to the laws of electrolysis. Typical anodes are zinc, aluminum, magnesium and their alloys. [1] The figure below (Figure 4.5) shows a sacrificial system schematically.

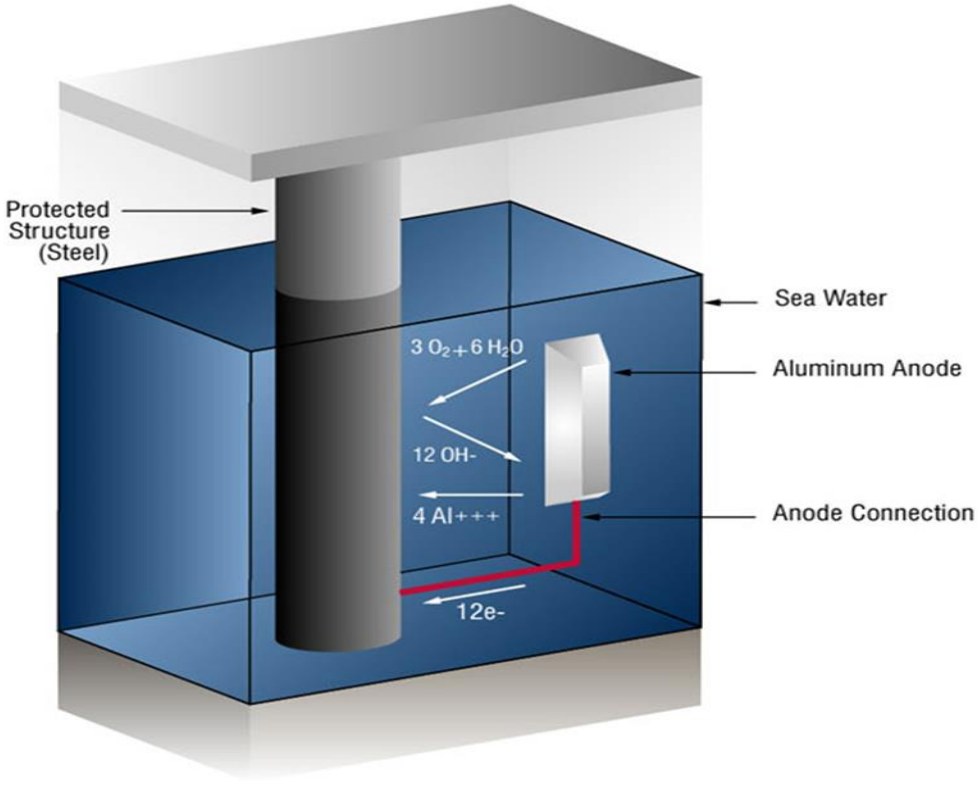

Figure 4.5: Sacrificial anode system in seawater

To understand the action of sacrificial anodes for cathodic protection it is necessary to have in mind the galvanic series of metals. The galvanic series for a few selected metals in sea water is shown in Table 4.1. When the tendency for metal to go into solution as metal ions increases (leaving an excess of electrons on the metal surface), i.e.

$$M-> Mn^{+} + ne^{-} \qquad (4.4.3)$$

the metal becomes more electronegative. Thus, since zinc, aluminium and magnesium are more electronegative than steel they are increasingly able to supply electrons to the more electropositive steel when in electrical contact in water, and will effect cathodic protection of the steel surface. Clearly, if steel was coupled to copper ins ea water, steel would supply electrons to copper which would become cathodically protected, and the corrosion of the steel would be enhanced.

Table 4.1: Galvanic series of some metals in sea water

Electropositive
Platinum
Titanium
Stainless steel
Monel
Copper
Lead
Iron, cast iron, or steel
Cadmium
Zinc
Aluminium
Magnesium
Electronegative

The reaction at the anode (equation 4.4.3) is the consumption of the anode to produce the electrons that the steel would be otherwise giving up.

The resistance of the concrete electrolyte is the crucial element to determine whether the use of sacrificial anodes is viable. In cases where the electrolyte resistance is too high, the effective potential difference between the steel and the anode may not be sufficient to adequately protect the structure. Thus, sacrificial anodes are very common for structures exposed to seawater and to other electrolytes that decrease the concrete resistivity.

The anodes are dissolved through anodic dissolution of the metal while oxygen reduction takes place at the surface of the steel structure. The supply of oxygen is what often limits the current density for oxygen reduction, which means that a limiting current of an almost constant value over a few hundreds of millivolts in potential is obtained at the surface of the steel structure. [7]

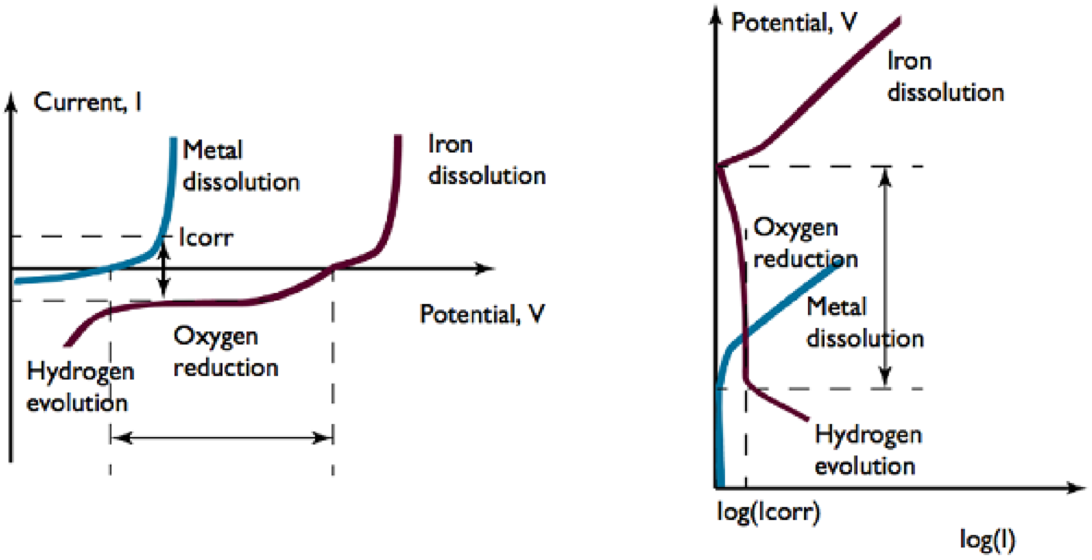

Figure 4.6*: Polarization behavior of the sacrificial anodes (blue) and steel surface (red)*

The figure above (Figure 4.6) shows the schematic polarization of the sacrificial anodes and of the oxygen reduction reaction at the surface of the steel structure. [6] The red curve represents the polarization of the steel surface while the blue curve is the polarization of the sacrificial anode. On the left, the currents at the steel structure (red) and at the sacrificial anodes (blue) are plotted as functions of the electric potential measured relative to a common reference. The plot to the right shows the electric potential as a function of the logarithm of the absolute value of the current. As shown in the left graphs, oxygen reduction is achieved at the steel surface along the range of the cathodic limiting current represented by the flat horizontal part of the red curve. In the right plot, the vertical part of the red curve represents oxygen reduction. The system operates at the point where the cathodic current (red) is equal in size (but opposite in sign) as the anodic current. The shape of the blue curve changes depending on the number and design of the anodes in the system, and the designer of the system needs to ensure that the different parts of the steel structure are well within the corrosion protected range of potentials (the “flat” part of the red cathodic curve); otherwise the structure is not fully protected and may start to corrode. The width of the oxygen reduction part of the curve is a few hundred millivolts. In addition, the anodes have to be able to deliver the required potential to keep the given current. The first step in the design of a cathodic protection system is therefore to investigate the potential of the steel structure assuming a constant cathodic current (oxygen reduction). The potential has to be well within the required range where oxygen reduction protects the structure and also avoiding hydrogen evolution, which may eventually cause hydrogen embrittlement.

The figures below (Figure 4.7 and Figure 4.8) show the model geometry. The sacrificial anodes are placed relatively close to the oil platform. The radius of the inner cylinder is chosen so that the main part of the charge transport occurs within this cylinder. The outer cylinder is modeled as an infinite Element Domain, which rescales the equations to represent an approximately 1000 times larger cylinder.

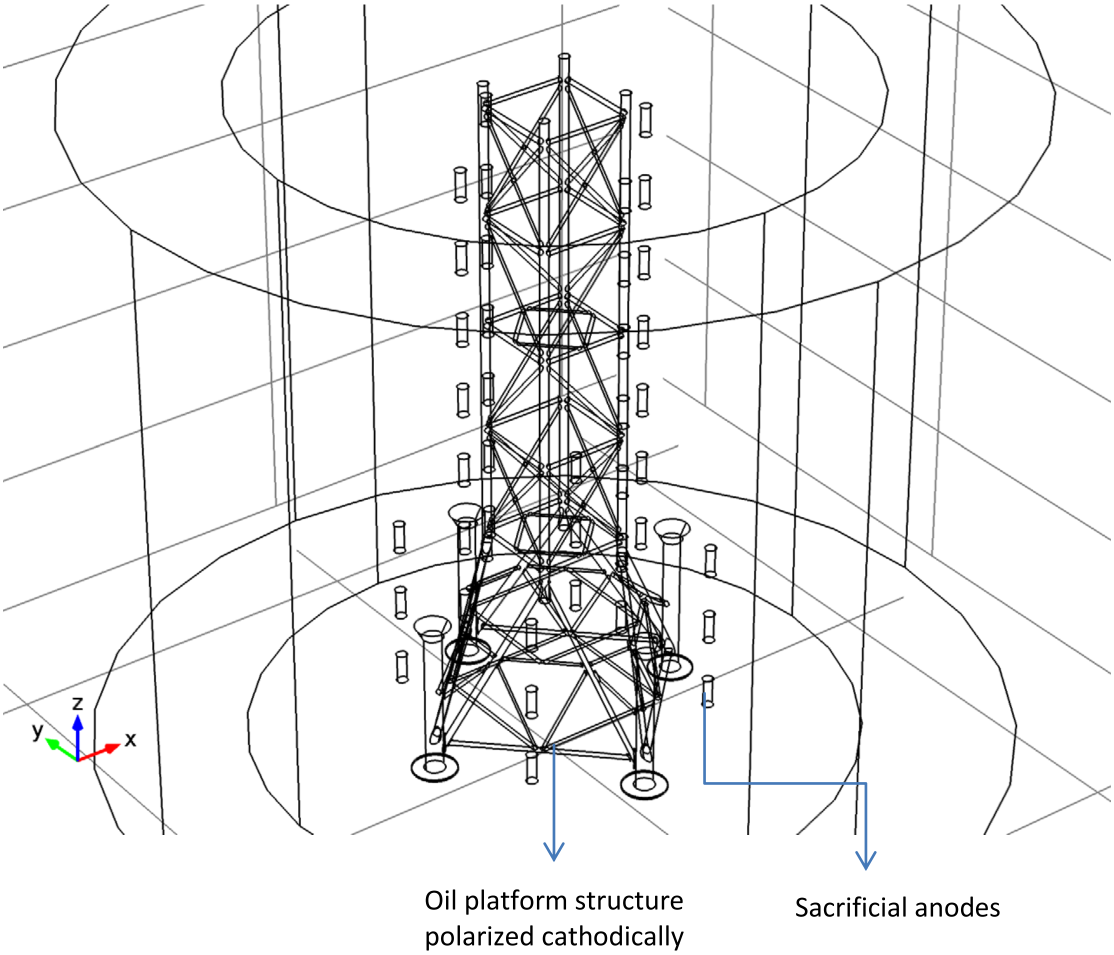

Figure 4.7*:* Model geometry

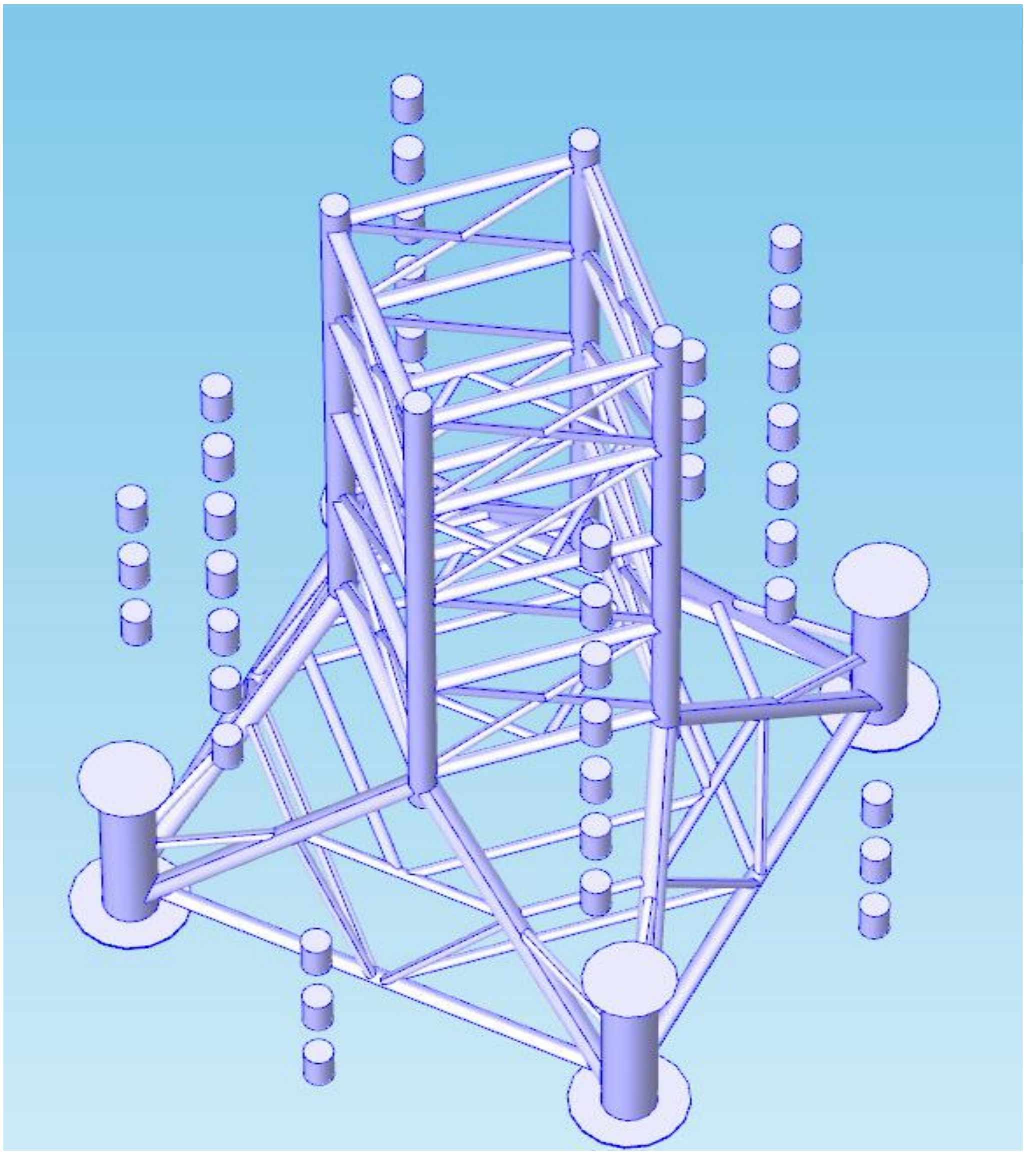

Figure 4.8*:* Close-up view of the cylindrical sacrificial anodes and the oil platform structure

At the sacrificial anode surfaces, a constant potential is set assuming a relatively fast kinetics. This assumption implies that a very small change in surface overpotential leads to a very large change in current density and it is therefore reasonable to set a constant potential. At the cathode surface, it is assumed that oxygen reduction takes place at a limiting current density, limited to the rate of transport of dissolved oxygen to the surface. This yields a constant normal current density boundary condition at the steel surfaces of the structure. All other boundaries are insulated boundaries. In seawater, the composition is assumed to vary to a very small extent and diffusion of the ions that carry the current is negligible compared to the contribution from migration of these ions in the electric field. This assumption, together with the boundary conditions, allows using a primary current density distribution analysis on the system where only the influence of ohmic effects in the given geometry are taken into account. The model can be easily extended to secondary current density distribution analysis in order to add the kinetics of the electrode reactions in a second stage. (A tertiary current density distribution analysis that also accounts for the transport of charged species is also possible in the Corrosion Module, although this would require the use of a different physics interface.)

Figure 4.9 shows the potential in the electrolyte at the surfaces on the steel structure and on the anodes. The potential on the steel structure surface varies several hundreds of millivolts, depending on position. The further the distance from an anode – the lower the potential, an expected result since the current in the electrolyte flows from the anodes to the cathode.

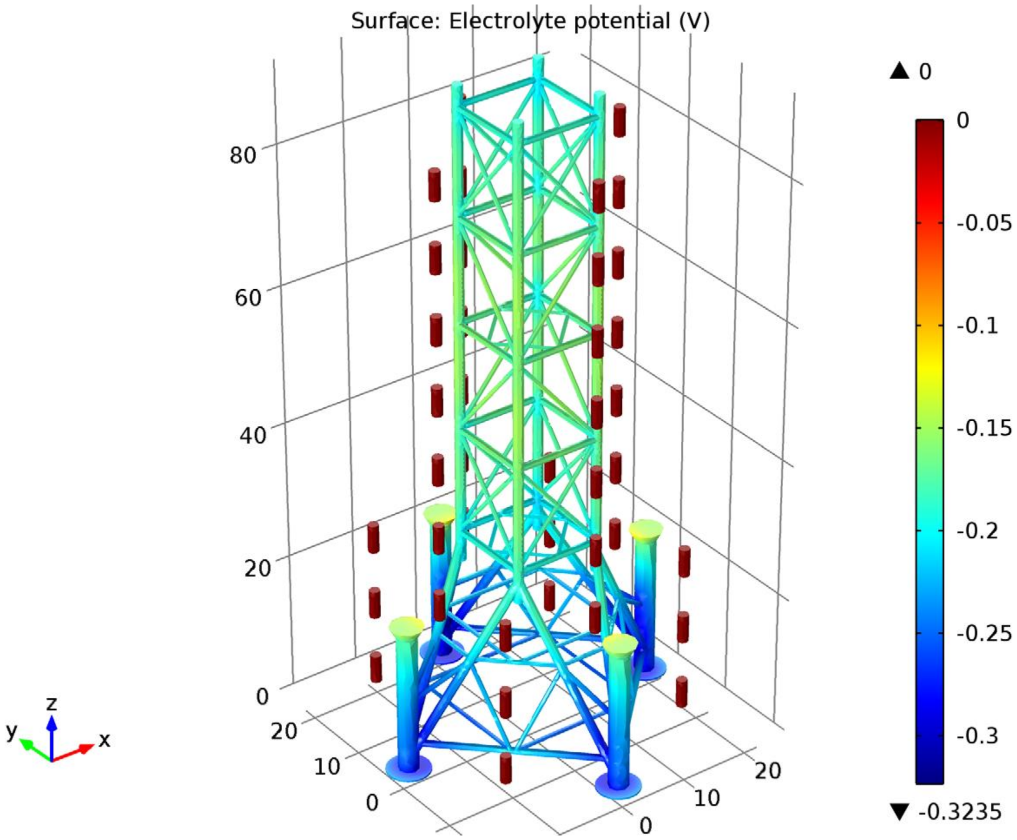

Figure 4.9: Electrolyte potential on the sacrificial anodes and on the platform

The figure below (Figure 4.10) shows a close-up of one of the structure legs. The inside bottom part of the leg has the lowest potential, indicating that this part of the structure will be the part most susceptible to corrosion.

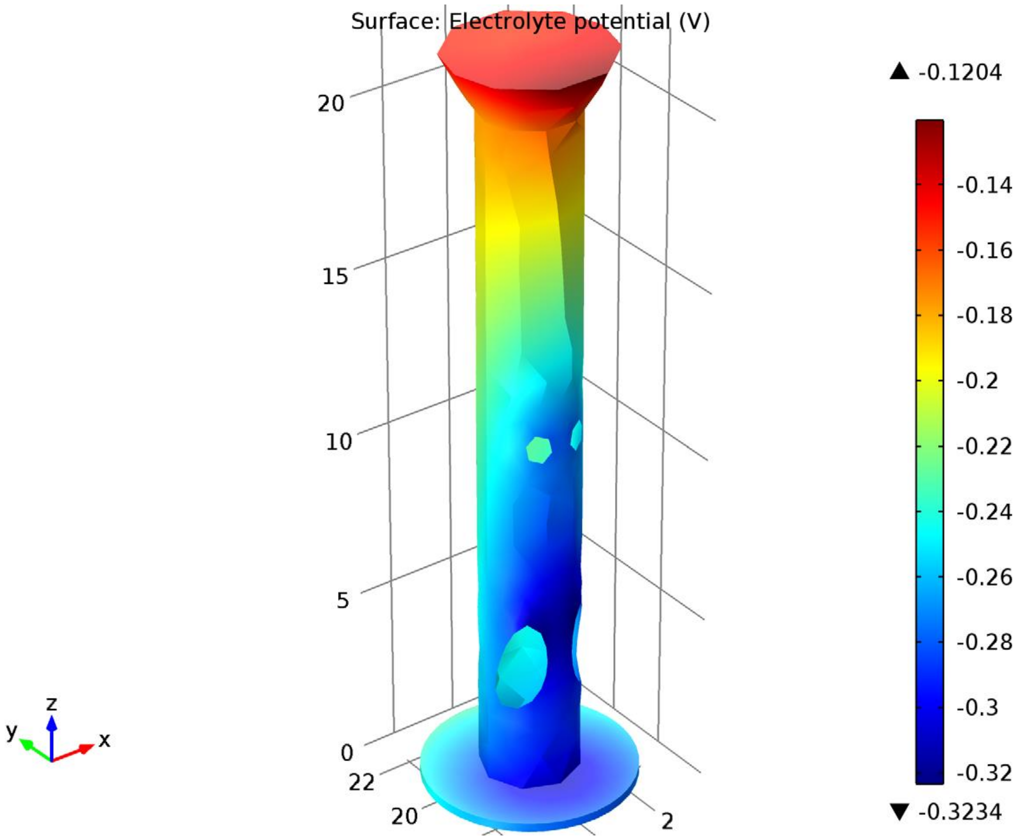

Figure 4.10: Electrolyte potential on one of the legs of the platform structure

Finally, the figure below (Figure 4.11) shows the current densities on the anodes, which are of interest because their magnitudes are directly proportional to the consumption rate of the anode metal. The highest current density for the anodes is about four times the lowest current density.

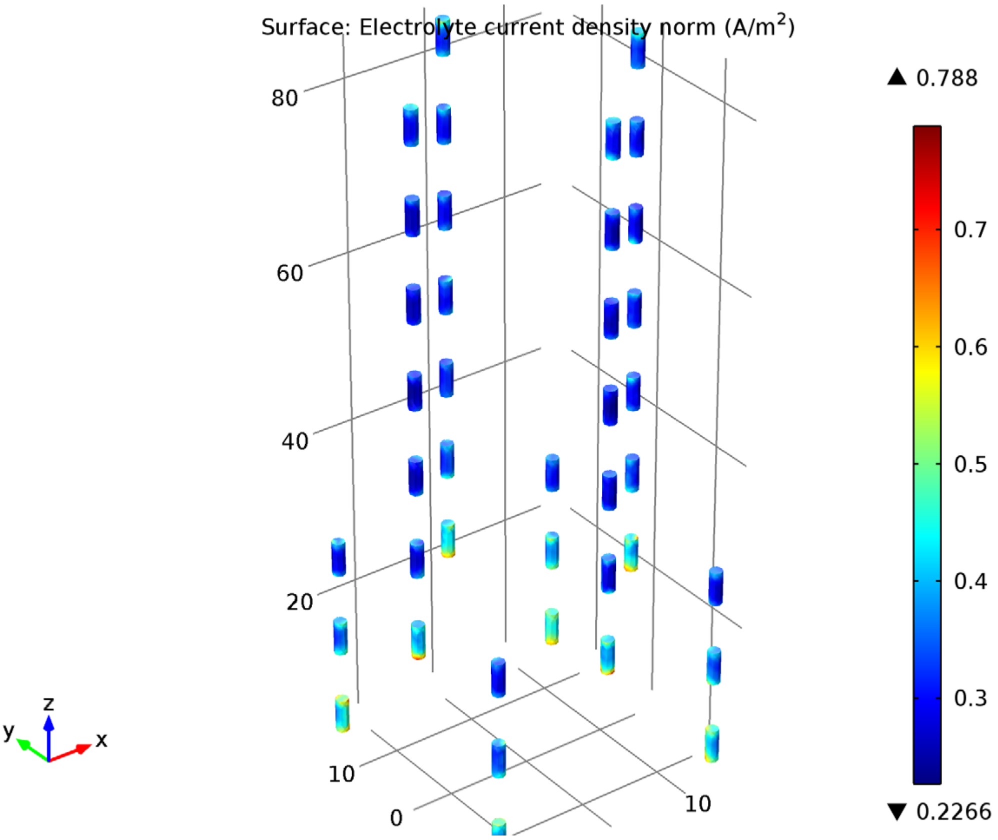

Figure 4.11: Current densities on the anodes

4.4.2.1 Types of Galvanic Anodes

Galvanic anodes for offshore applications are generally based on aluminium, magnesium or zinc. Aluminium based anodes are normally preferred due to their higher electrochemical capacity, ε $(^{A*h}/_{kg})$. [18] Nowadays, engineers don't use zinc anodes for environmental reasons. Some anode properties are shown in the Table 4.2 below.

Table 4.2: Properties of sacrificial anodes

Anode material	Density $(g * cm^{-3})$	Potential volts $(Cu/CuSO_4)$	Amp $(hrs * per * kg)$	Typical anode current density $(A * m^{-2})$
Zn	7.1	-1.10	780	0.5-2
Al	2.7	-1.15	2700	0.6-2.5
Mg	1.7	-1.55	1230	1.5-5.6

Sacrificial anodes are generally cast in three basic geometric shapes:

1. the slender, stand-off type
2. the bracelet type; and
3. the flat-plate, flush-mounted type

Stand-off and flush-mounted anodes may further be divided into "short" and "long", based on the length to width ratio. [18]

1. Stand-off anodes

The most common anode shape used for offshore structures is the long, slender type with a trapezoidal or circular cross-section with weight about 100kg (Figure 4.12). The principal advantages of this anode geometry are high current output and good current distribution for a given mass, noting that a flush-mounted anode with the same net anode mass will have a lower anode current output and lower utilization factor. Another advantage is the simple fabrication and casting requirements. [20]

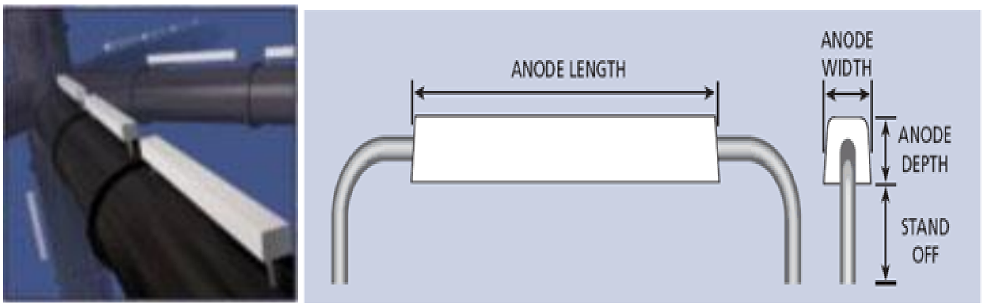

Figure 4.12: Stand-off anodes

2. Bracelet

Bracelet anodes are the most commonly used type for protection of submarine pipelines, for which their wrap-around construction is ideally suited (Figure 4.13). These anodes were primarily for pipelines but now they are used on platform legs in the upper zone, combining a high current-output-to-weight ratio with low drag.

Compared to long, slender anodes, bracelet anodes have low current – output-to – mass ratio. However, bracelet anodes do lend themselves to retrofitting on existing structures and to supplementing or replacing the original failed, deficient or end-of-life cathodic protection systems. [20] Long stand-off type anodes are usually preferred for relatively large anodes (about 100 kg and more) to be installed on platform substructures and subsea templates. A flush-mounted anode with the same net anode mass will have a lower anode current output and lower utilisation factor. [18]

Figure 4.13: Bracelet anodes

3. Flush mounted anodes

In general, flat-plate anodes are the best solution to complex fabrications where space limitations prevent the use of larger stand-off anodes or of the cathode current densities are low. All flush-mounted anodes should have a suitable coating system applied on the surface facing the protection object (Figure 4.14). This is to avoid build-up of anode corrosion products that could cause distortion and eventually fracture of the anode’s fastening devices. [20]

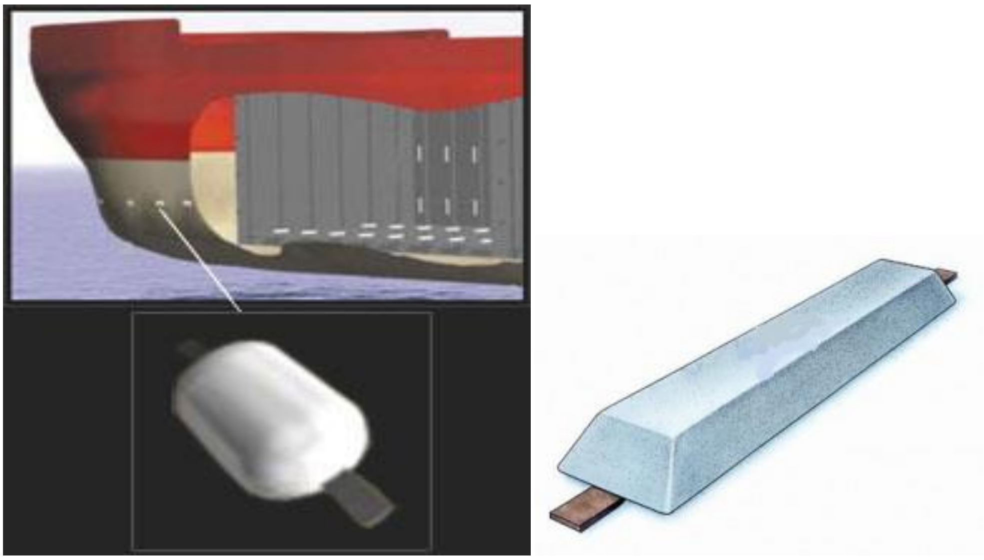

Figure 4.14: Flush mounted anodes

The anode must deliver adequate current to polarize the structure and build up cathodic chalks, but also must be capable of delivering the required mean current for the structure when 90% consumed. Moreover, the system as a whole must be adequate excess current demand over that originally catered for in the design so as to ensure that the system is not limited by the current output characteristics of the anodes. [3]

As a general rule:

The length of the anode determines how much current the anode can produce, and consequently, how many square feet of steel can be protected. The cross section (weight) determines how long the anode can sustain this level of protection.

4.4.3 Anode Type Selection

Selection of anode type is primarily determined by the size and geometrical configuration of the protection object, in addition to forces exerted on anodes during installation and operation. The anode type further affects the anode utilization factor and the anode current output in relation to weight. All platform anodes are either in trapezoidal or cylindrical cross section with a round solid bar or tubular steel inserts. Generally, anodes are selected based on cost, availability, performance, and reliability and they must be periodically inspected and replaced when consumed.

4.4.4 Anode Utilization Factor (u)

The anode utilization factor, u, is the fraction of anode material of an anode with a specific design that may be utilized for calculation of the net anode mass required to sustain protection throughout the design life of a CP system. When an anode is consumed to its utilization factor, the polarizing capacity (as determined by the anode current output) becomes unpredictable due to loss of support of anode material, or rapid increase of anode resistance due to other factors. The utilization factor is dependent on the anode design, particularly its dimensions and the location of anode cores. Unless otherwise agreed, the anode utilization factors in Table 4.3 shall be used for design calculations.

Generally, the utilization factor is a measure of the proportion of the anode, which can be expected to deliver adequate current at the end of the system's lifetime and is related to the reduced cross section and length of an almost fully consumed anode.

Table 4.3: Utilization factors for common anode geometries

Anode type	Anode Utilization Factor
Long Slender stand-off	0.90
Long1 flush mounted	0.85
Short2 flush mounted	0.80
Bracelet, half-shell type	0.80
Bracelet, segmented type	0.75
Long: Anode Length > 4 r thickness, Short: Anode Length < 4 r thickness	

When the anode has been consumed to its utilization factor, u, at the end of the design life, t (years), the remaining net anode mass, ma_f (kg), is given by:

$$ma_f = ma * (1 - u) \tag{4.4.4}$$

where:

ma = the net mass per anode (kg)

For long and short slender stand-off anodes consumed to their utilisation factor, a length reduction of 10% shall be assumed. Furthermore, assuming that the final anode shape is cylindrical, the final radius shall be calculated based on this length reduction, and the final anode mass/volume as explained below. For long and flush mounted anodes, the final shape shall be assumed to be a semi-cylinder and the final length and radius shall be calculated as above. For short flush-mounted anodes, bracelet anodes and other shapes mounted flush with the protection object, the final exposed area shall be assumed to be equivalent to the initial area facing the surface to be protected. [18]

4.4.5 Anode Resistance Formulas

Unless otherwise agreed, the anode resistance, Ra (ohm), shall be calculated using the formula in Table 4.4 that is applicable to the actual anode shape. Calculations shall be performed for the initial anode dimensions and for the estimated dimensions when the anode has been consumed to its utilization factor.

Table 4.4: Recommended Anode Resistance Formulae for CP Design Calculations

Anode Type	Resistance Formula
Long slender stand-off $L \geq 4r$	$Ra = \frac{\rho}{2\pi L}(\ln\frac{4L}{r} -1)$
Short slender stand-off $L< 4r$	$Ra= \frac{\rho}{2\pi L}[\ln\{\frac{2L}{r}(1+ \sqrt{1+\left(\frac{r}{2L}\right)}2 +\frac{r}{2L} - \sqrt{1+\left(\frac{r}{2L}\right)}]$
Long flush mounted $L \geq 4 \cdot$ width and $L \geq 4 \cdot$ thickness	$Ra = \frac{\rho}{2S}$
Short flush-mounted, bracelet and other types	$Ra = \frac{0.315*\rho}{\sqrt{A}}$
1) The equation is valid for anodes with minimum distance 0.30 m from protection object. For anode-to-object distance less than 0.30 m but minimum 0.15 m the same equation may be applied with a correction factor of 1.3 2) For non-cylindrical anodes: r = S/ 2 π where S(m) is the anode cross sectional periphery	

where:
L = Length of anode (m)
ρ = Assumed electrolyte resistivity of sea water (ohm-m)
r = The mean effective radius of the anode, $r = \sqrt{A/\pi * 60/100}$ m
A = The cross-section area of anode, m^2

Notice: The cross-section area of the anode to be used in determining the mean effective radius is that corresponding to the anodes consumed by 40%.

4.4.6 Seawater and Sediment Resistivity

The seawater resistivity, ρ (ohm-m), is a function of the seawater salinity and temperature. In the open sea, the salinity does not vary significantly and temperature is the main factor. The relationship between resistivity and temperature at a salinity of 30 to 40 ‰ (parts per thousand) is shown in Figure 4.15. Compared to seawater, the resistivity of marine sediments is higher by a factor ranging from about 2 for very soft clays to approximately 5 for sand. Unless sediment data for the location are available, the highest factor shall be assumed for calculation of the resistance of any buried anodes. [18]

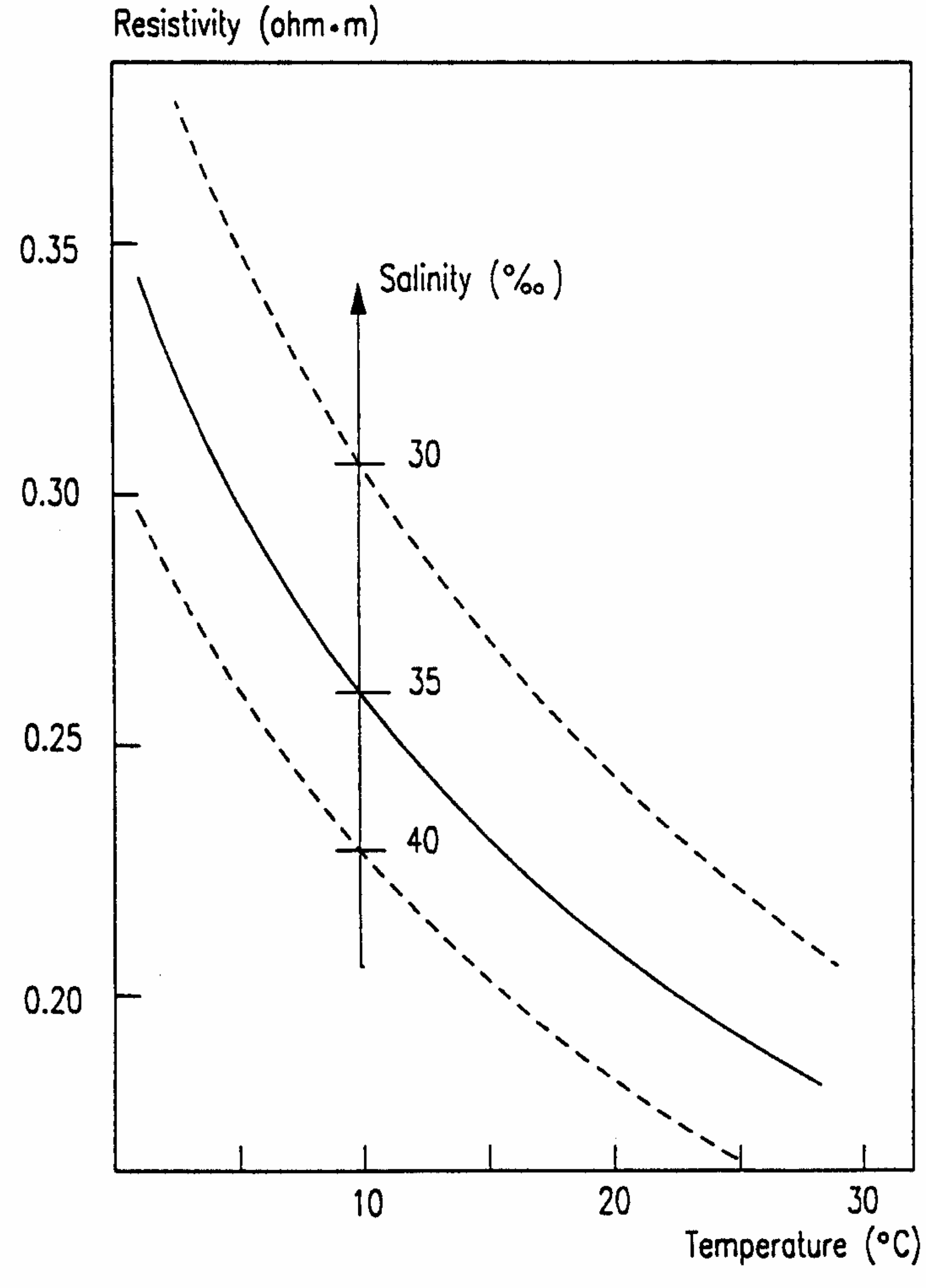

Figure 4.15: Seawater resistivity as a function of temperature for salinity 30 to 40 ‰.

4.4.7 Individual Anode Current Capacity

The individual anode current capacity, $Ca\ (A \cdot h)$, is given by:

$$Ca = ma * \varepsilon * u \tag{4.4.5}$$

where:

ma= the net mass per anode (kg)

In addition to the current requirements anode resistance and anode output need to be considered and may result in the need for additional anode or a change in anode design.

4.5 Choice of cathodic protection system

In the design of a cathodic-protection scheme, a decision must be made as to whether the scheme should be a sacrificial anode or impressed-current system or a mixture of the two systems.

4.5.1 Advantages of sacrificial anode systems

Sacrificial anode systems have the advantage of being:

1. simple to install,
2. independent of any source of electric power,
3. suitable for localized protection,
4. less liable to cause interaction on neighboring structures.

Cathodic protection with sacrificial anode is simpler and it is difficult to over-protect the structure and moderately easy to obtain a uniform electrode potential across the structure. The most severe limitation of the sacrificial anode is the small driving force which restricts its use to conductive environments or well-coated systems. To protect a large structure, such as a platform, with sacrificial anodes, a large number of them would need to be distributed along it, involving a multiplicity of electrical connections and considerable installation work.

4.5.2 Advantages of the impressed-current systems

The principle advantage of impressed current cathodic protection is its much greater output capacity as compared to galvanic anode systems. Therefore, whenever corrosion protection is desired for very large, poorly coated, or bare structures, impressed current is often the system choice.

Therefore, the amount of metal surface exposed to the corrosive environment is substantial and the amount of cathodic protection current required is typically in excess of 4 to 8 amperes for a typical service station facility. To generate a similar amount of current from a galvanic anode system, more than 100 magnesium anodes would typically be required. Thus, it is usually not practical or economic to use galvanic anodes to protect large, bare underground structure.

There are several important advantages to using impressed current anode systems:

(a) The large driving force available can protect a large, even uncoated, structure in high resistivity environments,

(b) Comparatively few anodes are needed,

(c) The voltage may be adjusted to allow for environmental and coating changes.

(d) Unlimited current output capacity: The amount of current that can be designed into an impressed current system can be from a few amperes to as much as several hundred amperes. The amount of current available will be a function of the number of anodes provided, the rectifier voltage and amperage capacity and the soil (electrolyte) resistivity in which the anodes are installed.

(e) Adjustable output capacity: The output of the rectifier power supply is easily adjusted to accommodate either changes in circuit resistance or current requirement. They can be provided with automatic control circuity to eliminate the need for manual adjustment.

(f) Lower cost per ampere of cathodic protection current Galvanic anode systems are significantly more expensive where amperes rather than milli-amperes of total current are required.

4.5.3 Disadvantages of the impressed-current systems

There are several significant disadvantages to the use of impressed current cathodic protection.

1. They are costlier if only a few milliamperes of current are required to protect a small or very well coated structure. Impressed current systems typically have a base cost of several thousand dollars. If only a few galvanic anodes are required for protection of a specific structure, this will often be the more economic choice.

2. Impressed current systems have a higher maintenance cost. Impressed current systems are inherently more prone to failure. Switches can be turned off and fuses can blow. Thus, the system needs to be monitored more frequently and some repair may be required once every several years.
3. Impressed current systems may create stray current corrosion in other nearby structures. This is an inherent potential problem with any impressed current system. This can sometimes be minimized through the use of distributed anode designs where the anodes are placed nearby the protected structures. [17]

4.5.4 Applications preferred of each method

Generally, sacrificial anode schemes have found favour for small well-coated low-current demand structures or for localised protection, with impressed-current schemes being utilized for large complex structures which may be bare or poorly coated. [11] However, in North Sea offshore work, it has been found economic to provide galvanic protection to large uncoated platforms and similar structures where the cost of coating is prohibitive. In addition, the galvanic anodes offer easily installed robust systems which, being independent of a power source, provide protection immediately on “float-out” of the structure.

The driving voltage of sacrificial anodes is now compared with impressed-current anodes, and sacrificial anodes must be located close to the structure being protected. Although almost any piece of zinc etc could provide cathodic protection over a short period of time, cathodic protection schemes are usually required to operate over periods of several years. Anodes can lose their activity and become passivated, developing a non-conducting film on their surfaces so that they no longer are able to supply current. This can be avoided by careful control of the concentrations of trace impurities in the anode materials, and by alloying. For zinc anodes the level of iron, for example, must be kept below 0.005% for satisfactory long-term operation of the anodes.

To prevent passivation of aluminium anodes, alloying with, for example, indium has been found to be successful. The previously successful alloy with mercury is now disliked on environmental grounds.

For marine applications, galvanic anode cathodic protection systems were the norm because they were relatively easy to maintain and are reliable. Nowadays, ICCP method is the norm because the cost of sacrificial anodes has increased a lot.

4.6 Conjunction with coatings

The provision of an insulating coating to the structure will greatly reduce the current demand for cathodic protection. When first applied, coatings will often contain flaws, and in service, further defects will develop over a period of time. The conjoint use of coatings and cathodic protection takes advantage of the most attractive features of each method of corrosion control. Thus, the bulk of the protection is provided by the coating and cathodic protection provides protection to flaws in the coating. As the coating degrades with time, the activity of the cathodic protection system develops to protect the deficiencies in the coating. A combination of coating and cathodic protection will normally result in the most economic protection system.

4.6.1 Coating Breakdown Factor

The coating breakdown factor is a function of coating properties, operational parameters and time. As a simple engineering approach, f_c can be expressed as:

$$f_c = a + b * t \tag{4.6.1}$$

where:

t = the coating lifetime (years),

a, b = constants that are dependent on coating properties and the environment.

The coating breakdown factor, f_c, describes the anticipated reduction in cathodic current density due to the application of an electrically insulating coating.

When f_c = 0, the coating is 100% electrically insulating, thus decreasing the cathodic current density to zero.

When f_c = 1, the coating has no current reducing properties. [6, 18]

4.7 Calcareous deposits

Seawater has an alkaline pH and therefore, calcium and magnesium ions present in seawater combine with $(OH)^-$ and $(HCO3)^-$ ions (also present in sea water) forming white calcareous deposits on the cathode surface:

$$Ca2^+ + HCO3^- + OH^- -> H_2O + CaCO_3 \tag{4.7.1}$$

$$Mg_2^+ + 20H^- -> Mg(OH)_2 \tag{4.7.2}$$

As a result, a thin film forms on the cathode surface. These calcareous deposits act as a diffusion barrier to dissolved oxygen ingress. Limiting the oxygen availability causes the current demand of the system to decrease; and, consequently, the service life of the galvanic anodes is prolonged. [2] In sea water, cathodic protection of bare steel is economic because of the formation of calcareous deposits. The alkali formed at the surface of a protected structure reacts with bicarbonate ions present in sea water to form carbonate ions (reaction 4.7.3) which, in turn, precipitate as insoluble calcium carbonate (reaction 4.7.4) on the surface of the metal [5]

$$OH^- + HCO_3 -> CO_3^{-2} + H_2O \tag{4.7.3}$$

$$CO_3^{-2} + Ca^{+2} -> CaCO_3 \tag{4.7.4}$$

5 CP DESIGN PRACTICES AND PROTOCOL

Chapter five refers to design protocols which are available from the National Association of Corrosion Engineers (NACE International), Det norske Veritas (DnV) and the International Standardization Organization (ISO). It describes the basic requirements and considerations on designing cathodic protection systems.

5.1 Traditional cathodic protection design

Traditionally, the design of cathodic protection systems is decided on the following procedures: [16]

a. Estimation of anode current output by using anode resistance formulae and fixed driving force between the anodes and the cathode (structure)
b. Estimation of cathode current requirement from tabulated values
c. Placement of anodes on the structure based on previous experience with similar systems in similar environments
d. Estimation of the system life time essentially by using Faraday’s law.

To design cathodic protection systems information on the total current requirement, resistance, expected life, and anode current out are needed. Table 5.1 shows some typical values used in cathodic protection design.

Table 5.1: Cathodic protection design parameters and coatings design considerations

Design parameter	Typical Value
Seawater Resistivity	20 – 25 $ohm - cm$
Saline Mud	100 – 150 $ohm - cm$
Anode open circuit potential - buried	-1.05 $V\ (Ag/AgCl)$
Anode open circuit potential - seawater	-0.95 $V\ (Ag/AgCl)$
Anode Consumption	1280 $A\ hours/\ pound$
Anode Utilization Factor	0.80
Coating Breakdown Factor (FBE)	0.5% to 1.0% (initial) 10% (after 30 years)
Insulation Breakdown Factor	0.5% to 1.0% (initial) 3% (after 30 years)
Neoprene Breakdown factor	0.5% to 1.0% (initial) 5% (after 30 years)
Design current density for bare steel in seawater	$12mA/ft^2$ (initial) $7\ mA/ft^2$ (after polarization)
Design current density in sand or mud	$2\ mA/ft^2$ (initial and after polarization)

5.2 Design protocols

Designing CP systems requires knowledge of factors such as current density demand, circuit resistance, and electrolyte resistivity. Design protocols are available from the National Association of Corrosion Engineers (NACE International), Det norske Veritas (DnV), and the International Standardization Organization (ISO).

The following normative documents contain the requirements for the application and the design of cathodic protection systems:

1. American Petroleum Institute (API)
   API RP 580: Risk Based Inspection & Integrity Management

2. BP Integrity Management (IM) Standard
   a. GP 06-36: Guidance on Practice for Cathodic Protection – Maintenance and Monitoring
   b. GIS 06-311: Guidance on Industry Standard for Cathodic Protection Procurement
   c. GIS 06-601: Guidance on Industry Standard for for Coating of Metal Surfaces and Equipment
   d. Euro Norm (EN)

   e. EN 12473: General Principles of Cathodic Protection in Sea Water
   f. EN 12954: Cathodic Protection of Buried or Immersed Metallic Structures - General Principles and Applications for Pipelines

3. Det Norske Veritas (DNV)
   a. DNV RP-B401: Recommended Practice Cathodic Protection Design
   b. DNV RP-F103: Recommended Practice Cathodic Protection of Submarine Pipelines by Galvanic Anodes

4. International Organization for Standardization (ISO)
   ISO 15582-2: Petroleum and Natural Gas Industries – Cathodic Protection of Transportation Systems – Part 2: Offshore Pipelines

5. NACE International (NACE)
   a. NACE RP0169: Control of External Corrosion on Underground or Submerged Metallic Piping Systems
   b. NACE RP0176: Corrosion Control of Steel Fixed Offshore Structures Associated with Petroleum Production
   c. NACE RP0186: Application of Cathodic Protection for Well Casing
   d. NACE RP0196: Galvanic Anode Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks
   e. NACE RP0387: Metallurgical and Inspection Requirements for Cast Sacrificial Anodes for Offshore Applications.
   f. NACE RP0388: Impressed Current Cathodic Protection of Internal Submerged Surfaces of Carbon Steel Water Storage Tanks
   g. NACE RP 0492: Metallurgical and Inspection Requirements for Offshore Pipeline Bracelet Anodes.
   h. NACE TM0190: Impressed Current Laboratory Testing of Aluminum Alloy Anodes

6. NORSOK
   NORSOK Std M-503: Cathodic Protection

These standards recommend designing CP systems based on three current density values: an initial, mean, and final.

5.3 Design current densities

Current density, i_c , refers to cathodic protection current per unit surface area (A/m2). The 'initial' and 'final' design current densities, i_{ci} (initial) and i_{cf} (final), respectively, give a measure of the anticipated cathodic current density demand to achieve cathodic protection of a bare metal surface within a reasonably short period of time. They are used to calculate the initial and final current demands which determine the number and sizing of anodes. The effect of any coating on current demand is taken into account by application of a 'coating breakdown factor'.

5.3.1 Initial Design Current Density

The initial design current density refers to the cathodic current density that is required to effect polarization of an initially bare metal surface, typically for structural steel surfaces with some rusting and/or mill scale. [18] The initial design cathodic current density is necessarily higher than the final design current density because the calcareous scale and possibly marine fouling layer developed during this initial phase reduce the subsequent current demand (i.e. the 'polarization resistance' is reduced).

A sufficient initial design current density enables rapid formation of protective calcareous scale and hence efficient polarization.

5.3.2 Final Design Current Density

The final design current density refers to metal surfaces with established calcareous scale and marine growth. It takes into account the current density required to re-polarize a structure if such layers are partly damaged, e.g. by periodic removal of marine growth. [18] An appropriate final design current density (and hence CP polarizing capacity) will further ensure that the protection object remains polarized to a potential of -0.95 to -1.05 V throughout the design life. In this potential range, the current density demand for maintenance of CP is lowest.

5.3.3 Mean Design Current Density

The mean (or 'maintenance') design current density, i_{cm} (A/m^2), is a measure of the anticipated cathodic current density once the CP system has attained its steady-state protection potential; this is typically 0.15 to 0.20 V more negative than the design protective potential. [18] Design current density recommendations are based on experience and are broken down according to environmental region, as shown in Table 5.2 below. [2]

Table 5.2: Summary of recommended design current densities for bare steel

Organisation	Location	Water Temp.(◦C)	Design Current Density(mA/m^2)		
			Initial	Mean	Final
NACE International	Gulf of Mexico	22	110	55	75
	U.S. West Coast	15	150	90	100
	N. North Sea	0-12	180	90	120
	S.North Sea	0-12	150	90	100
	Arabian Gulf	30	130	65	90
	Cook Inlet	2	430	380	380
	Buried/Mud Zone	All	10-30	10-30	10-30
DnV	Tropical	>20	150/130	70/60	90/80
	Sub-Tropical	12-20	170/150	80/70	110/90
	Temperate	7-12	200/180	100/80	130/110
	Arctic	<7	250/220	120/100	170/130
	Buried/Mud Zone	All	20	20	20
ISO	Non-Buried	>20	-	70/60	90/80
		12-20	-	80/70	110/90
		7-12	-	100/80	130/110
		<7	-	120/80	170/130
	Buried/Mud Zone	All	20	20	20

The current density required to maintain the protection potential is very dependent on local conditions. Increased availability of oxygen at the surface of the metal will directly increase current density. Increased availability of oxygen may occur because of increased concentration of oxygen in the environment, increased water flow or turbulence. Thus, current densities to structures in sea water, rivers, etc are likely to vary continuously. The pH of the environment will also be important. The presence of coatings, marine fouling, and calcareous deposits will have a profound effect on current density. [5]

5.4 Basic requirements for cathodic protection

The essential features of cathodic protection to metals that are surrounded by a conducting electrolyte, in each of the two types of system are as follows:

1. A galvanic system requires:
    - i. Sacrificial anodes
    - ii. Direct welding to the structure or a conductor connecting the anode to the structure
    - iii. Secure and minimum resistance connections between conductor and structure, and between conductor and anode.
2. An impressed-current system requires:
    - i. Inert anodes (clusters of which, connected together often in a backfill, are called the“groundbed”).
    - ii. A dc power source.
    - iii. Electrically well insulated, minimum resistance and secure conductors between anodes and power source.
    - iv. Secure and minimum resistance connections between power source and structure. In both cases, fundamental design decisions must be made to select the type of system and the most suitable type of anode appropriate to that system. Also required, is the determination of the size and number of the power sources, or sacrificial anodes, and their distribution on the structure.

5.5 Current demand calculations (I_c)

Having decided on the appropriate current density (i_c), the total anode current can be determined from the area of the structure (A_c) and the coating breakdown factor, f_c, using the following equation.

$$I_c = A_c * i_c * f_c \tag{5.5.1}$$

Notice: In order to select the best size and shape of anode, the total current demand of the structure both at the beginning and end of its life must be considered.

5.6 Basic considerations when designing sacrificial anode systems

In a sacrificial cathodic protection system, the total current demand required is calculated by:

$$I = \nabla V / R \tag{5.6.1}$$

where:
∇V = Driving voltage (potential difference) between protected steel potential and anode closed circuit potential (V), and
R = Total circuit resistance (ohms)

Initially, current will be high because the difference in potential between the anode and cathode are high, but as the potential difference decreases due to the effect of the current flow onto the cathode, the current gradually decreases due to polarization of the cathode. The circuit resistance includes both the water path and the metal path, which includes any cable in the circuit. The dominant value here is the resistance of the anode to the seawater.

For most applications, the metal resistance is so small compared to the water resistance that it can be ignored (although this is not true for sleds or long pipelines protected from both ends). In general, long, thin anodes have lower resistance than short, fat anodes. They will discharge more current but will not last as long.

Therefore, a cathodic-protection designer must size the anodes so that they have the right shape and surface area to discharge enough current to protect the structure and enough weight to last the desired lifetime when discharging this current.

5.6.1 Galvanic Anode Material Design Parameters

The CP design parameters related to anode material performance are:

1. design electrochemical capacity, ε (Ah / kg)
2. design closed circuit anode potential, $E^o\ a$ (V)

1. Design Electrochemical Capacity, ε (Ah / kg)

The capacity of an anode alloy is a measure of the quantity of electricity; which the material will give as useable protection current per unit weight of alloy corroded in unit time. The design values for electrochemical capacity, ε (Ah / kg), in Table 5.3 shall be used for design unless otherwise specified or accepted by Owner. The data are applicable for ambient temperature seawater (i.e. up to 30°C as a yearly mean value).

Data on anode electrochemical efficiency from short-term laboratory examinations of galvanic anode materials will typically result in values close to the theoretical limit (e.g. ≥ 2,500 Ah/kg for Al-Zn-In material). This is due to the relatively high anodic current densities that are utilized for testing. Such data shall not replace the recommended design values for electrochemical capacity.

2. Design Closed Circuit Anode Potential, $E^o\ a\ (V)$

The design values for closed circuit anode potential, $E^o\ a\ (V)$, in Table 5.3 shall be used for design. The data are applicable for all ambient seawater temperatures (i.e. max 30°C yearly average).

Table 5.3: Recommended design electrochemical capacity and design closed circuit potential for anode materials at seawater ambient temperatures [19]

Anode Material Type	Environment	Electrochemical Capacity (Ah/kg)	Closed Circuit Potential (V)
Al-based	seawater	2,000	-1.05
Zn-based	seawater	780	-1.00

The design electrochemical capacity, $\varepsilon\ (Ah\ /kg)$, and design closed circuit anode potential, $E^o\ a\ (V)$ are used to calculate

1. the design anode current output and
2. the required net anode mass using Ohm's and Faraday's laws, respectively.

Required Total Anode Weight (kg)

If a sacrificial anode system is chosen, the weight of materials required to provide the protection current for the protected lifetime of the structure is calculated from a knowledge of the current demand and also the specific electrochemical properties of the anode alloys.

The mass of sacrificial anode alloys required will be given by:

$$W\ = (Y * 8.760 * I_C)/(u *\ \varepsilon) \tag{5.6.2}$$

where:

Y = Design Life (Years)

I_C = Current Demand (A)

u = Anode utilization factor (Table 4.3)

ε = Capacity of material $(Amp\ hrs/kg)$

The calculated weight of anode alloy cannot be installed all in one piece but must be distributed over the structure in the form of smaller anodes to ensure uniform distribution of current.

5.6.2 Number of Anodes (Pcs)

The total number of sacrificial required anodes are calculated as:

$$N_{total} = (W_{an.total})/(W_{anode}) \qquad (5.6.3)$$

where:
$W_{an.total}$ = the total weight (kg)
W_{anode}= the weight of each individual anode, (kg/Pc).

Or by the following equation:

$$N_{total} = I_c/I \qquad (5.6.4)$$

where:
I_c = Required total current (A)
I = Individual anode output current (A/Pc)

Once the number of anodes required is calculated the spacing between anodes can be calculated. Normally the number of anodes is rounded up to accommodate the spacing between girth welds.

5.6.3 Distribution of Anodes

The calculated number of anodes, N, for a CP unit shall be distributed to provide a uniform current distribution, taking into account the current demand of individual members due to different surface areas and any coatings used. On platform substructures, special areas to be considered when distributing anodes are e.g. nodes, pile guides and conductor bundles. The location of all individual anodes shall be shown on drawings.

Anodes shall be located with sufficient spacing between each other to avoid interaction effects that reduce the useful current output. As far as practical, anodes shall be located so that those of its surfaces intended for current output are not in close proximity to structural members, reducing the current output. [16]

With the exception of very large anodes, shielding and interference effects become insignificant at a distance of about 0.5 meter or more. If anodes are suspected to interfere, a conservative approach may be to consider two adjacent anodes as one long anode, or as one wide anode, depending on their location in relation to each other.

5.6.4 Quality Check

1. Required Weight(kg) < Actual Total Weight (kg)
   where Actual Total Weight = N* Anode mass

2. Required Current (A) < Actual Total Current (A)
   where Actual Total Current= N* Anode Output

5.7 Impressed current cathodic protection system design

Current demand in a ICCP system is calculated similar to the sacrificial current demand. The impressed current can be provided on shore and/or at the operating platform. ICCP has the added advantage of being able to change the current output. During initial startup of the CP system a higher current can be supplied to increase the rate of polarization.

5.8 Protection potentials

We can verify that there's enough current by measuring the potential of the steel against a standard reference electrode, usually silver silver/chloride (Ag/AgCl sw.), but sometimes zinc (sw.). The reference electrode should be very close to the surface whose potential is being measured.

Current flow onto any metal will shift its normal potential in the negative direction. History has shown that if steel receives enough current to shift the potential to (-) 0.800 V vs. silver / silver chloride (Ag / AgCl), the corrosion is essentially stopped. Due to the nature of the films which form, the minimum (-0.800 V) potential is rarely optimum, so designers try to achieve a potential between (-) 0.950 V and (-) 1.000 V vs. Ag/AgCl sw. For steel in an aerobic electrolyte of nearly neutral pH a commonly accepted protection potential is -850 mV; when exposed to sulphate-reducing bacteria a potential of –950 mV would be required. Both values are referred to a copper/copper sulphate electrode. Special techniques have been applied to control the CP protective potential to a less negative range (e.g. -0.80 to -0.90V), including the use of diodes and special anode alloys, but practical experience is limited. [18] A detailed summary of protection potentials for steel in seawater is provided in Table 5.4.

Table 5.4: Potential values for corrosion and protection of steel in seawater

V ref. Ag/AgCl	Condition	V ref. Zn
	Heavy Corrosion	
-0.60	Freely Corroding Steel	+0.50
-0.70	Some Protection	+0.40
-0.80	Cathodic Protection	+0.30
-0.90	Some Over Protection	+0.20
-1.00		+0.10
-1.10	Over Protection May Cause Paint Blistering and Flaking	0.00
-1.20		-0.10
-1.30		-0.20
-1.40		-0.30
-1.50		-0.40

5.9 Design life

The design life of a CP system is normally specified by Owner, taking into account the likelihood of the design life of the protection object being extended. The design life shall further take into account any period of time when the CP system will be active prior to operation of the protection object.

Maintenance and repair of CP systems for fixed offshore structures are generally very costly and sometimes impractical. It is therefore normal practice to apply at least the same anode design life as for the protection object. However, in certain circumstances planned retrofitting of sacrificial anodes may be an economically viable alternative to the installation of very large anodes initially. This alternative should then be planned such that necessary provisions for retrofitting are made during the initial design and fabrication. [18]

5.10 Parameters affecting cathodic protection

The major seawater parameters affecting CP are:

a. dissolved oxygen content
b. sea currents
c. temperature
d. marine growth
e. salinity

In addition, variations in seawater pH and carbonate content are considered factors which affect the formation of calcareous layers associated with CP and thus the current needed to achieve and to maintain CP of bare metal surfaces. The above parameters are interrelated and vary with geographical location, depth and season. [18]

6 CONCLUSION

Corrosion plays a pivotal role in the engineering world. Engineers of all disciplines must consider the dangers that this phenomenon can incur. Corrosion is likely to occur at potentials which are more positive than the protected value. The most widely used corrosion mitigation techniques such as coatings and cathodic protection are analyzed.

Protective coatings have always been a pivotal part of corrosion mitigation. This is because coatings can be applied to almost any material and can protect it under virtually all environmental conditions. The use of coatings for corrosion prevention is also examined. It is clearly shown in the paper that coatings provide the most effective protection when they are used in combination with a proper CP system. The provision of an insulating coating to the structure will greatly reduce the current demand for cathodic protection and the conjoint use of coatings and cathodic protection takes advantage of the most attractive features of each method of corrosion control. A combination of coating and cathodic protection will normally result in the most economic protection system.

A general review of cathodic protection methods has been presented. The two mains methods of cathodic protection, namely SACP (Sacrificial Anode Cathodic Protection) and ICCP (Impressed Current Cathodic Protection), have described analytically. Impressed current CP systems use an external DC current source and a variety of anode materials to supply the cathodic current. Sacrificial anode CP systems generate the cathodic current from the corrosion of metals less noble than the metal to be protected. Unlike the Impressed Current method, the use of sacrificial anodes does not require an external power supply. Instead, it utilizes the natural tendency of electron flow from negative to positive potential to drive the current.

The main advantage of Sacrificial Anodes CP systems over Impressed Current CP systems is that they do not require a power supply. Impressed Current CP systems require more monitoring than Sacrificial Anodes CP systems. Sacrificial Anodes CP systems are, however, limited in the current and voltage that they can produce. Impressed Current CP systems provide greater flexibility because the current can be easily adjusted. While sacrificial anodes corrode, requiring periodic replacement, the service life of the anodes used for Impressed Current CP systems is usually much longer. Nowadays, it is more economical to use sacrificial anodes for small structures and impressed current for large because the cost of anodes has increased. In the case of impressed current system, the major problems are mechanical and electrical rather than inadequate current distribution.

The choice between impressed and sacrificial cathodic protection depends many factors and may be just personal preference. There are, however, situations where one or the other provides the correct choice. The advantages and disadvantages of each type of CP system are described in Table 6.1.

Table 6.1: Advantages and disadvantages of Sacrificial Anode and Impressed Current CP systems

Sacrificial CP	**Impressed Current CP**
Advantages	
Self contained	Variable control of current and potential
Can be self adjusting	Light weight and fewer anodes
Simple to install	Long life with inert anodes
Needs no supervision	Can be automated
Polarity of connections always correct	Varied anode geometry
Disadvantages	
No variable control	Requires external power source
Anodes add weight	Higher initial cost
Anodes have finite life	Complex installation and maintenance
Expensive method of generating electricity	Anodes require dielectric shields
Small lead resistance reduces current	Expensive method because of the equipment

The design process for a corrosion protection system for offshore structures will now be discussed according to the widely used DNV-RP-B401 recommended industry practice. Although many of the considerations here deal with extreme environmental conditions, the process can still be applicable to multiple civil engineering structures.

The first step for the design of cathodic protection is to divide the offshore structure into several sections or zone. Each zone requires a different systematic approach. The three major zones are atmospheric, splash, and submerged.

The atmospheric zone refers to the section of the structure which is solely exposed to air. This zone experiences fairly low corrosion rates and does not require cathodic protection since a suitable coating system is enough to provide adequate corrosion control.

The splash zone is the area between the atmospheric and submerged zone. This section becomes wetted by the constant rise and fall of the tide as well as the effects of ocean wind. As mentioned before, even though this area experiences the highest corrosion rate, the use of a cathodic protection system combined with a coating system would be inefficient as the area would not be in constant contact with an electrolyte. It is important to select a suitable material that can be applied to the splash zone to form a stable electrolyte layer. In case of the part of the structure is wrapped with one layer of cotton, linen, dacron or chemical fiber, the protection efficiency by sacrificial anode in splash zone is high. These kinds of fabrics have the ability of preserving seawater when the part of the structure is moving out the seawater and as a result the sacrificial anode still function. It has been observed that linen is the best among the four kinds of fabrics and it has the best seawater absorbing capacity.

The submerged zone is below the splash zone and refers to part of the structure that is completely exposed to the electrolyte (seawater). In this zone use of a high performance coating system supplemented with cathodic protection is highly desired to achieve full cathodic protection.

Determination of the correct potential that the CP system requires to maintain proper protection is another essential initial step. Generally, the range of optimum potentials is between -950 mV to -1000 mV with reference to a silver/silver chloride standard electrode. It is important to note that potentials may also vary based on the standard reference electrode being used.

One of the main challenges in cathodic protection system design is finding the proper current density and demand. In order to ensure protection over the entire design life, engineers must perform several calculations to estimate the correct amount of current the structure will need throughout the different stages of its lifetime. The current density demand is separated into three stages: initial, mean, and final.

When the structure is first immersed in the electrolyte, an initial current is needed to polarize the steel as quickly as possible. This stage usually requires the highest level of current demand, which results from the initial high potential difference between the anode and cathode until polarization is achieved. The final current density required refers to the stage of a structure's life when calcareous scales have formed on the surface of the metal in addition to marine growth. It is calculated in order to determine the amount of current needed to re-polarize the structure if those layers were removed or damaged due to periodic maintenance or storms. The mean current density is also known as the maintenance current density.

A key value that must be calculated is the current demand (Ic) for each stage of a structure's design life. This demand is the product of the specific area to be protected (Ac), the relevant current density (ic), and the coating breakdown factor (fc).

Selection of the type of anode is another important step in the design process. The three major types of anodes are standoff, flush-mounted, and bracelet. For offshore structures, it is common to attach long, standoff anodes weighing up to one ton. Based on this selection, the anode resistance, utilization factor, and electrochemical capacity can then be determined. The current output from an anode is determined by anode residence (R), and driving potential (V), using the Ohm's Law.

The CP calculation procedure has also been explained and it was shown that Cathodic Protection calculations greatly depend on the area to be protected and the current density requirement of the structure. The CP system must be designed to provide the required current to every part of the structure for the required design life. This requires determining anode size, weight, number, and distribution.

The calculations for Impressed Current CP systems are relatively simple. In this case, it is only necessary to match the number of anodes of known current output to the total current demand of the structure, and to be sure that the anode distribution insures an even and well balanced current distribution.

The calculations for Sacrificial CP systems are a little more complex. Not only must the number of anodes satisfy the current demand of the structure, but they must also have sufficient mass to provide electricity for the design life of the structure. Sacrificial CP design requires that the weight of anode material is sufficient to supply current for the design life of the structure. The formula which is calculating the weight of anode material is analyzed. Due to practical considerations, anode selection may ultimately be determined by commercial availability. It is often too expensive to customize anode size and geometry for one job. Therefore, except for large and specialized requirements, CP design centers around standard, commercially available anode types.

Cathodic protection is a highly adaptable and effective means of preventing corrosion on a variety of underground or underwater structures. When a system is designed, installed and maintained properly, cathodic protection is one of the most effective and economical methods of preventing corrosion. It is important to check and monitorize a cathodic protection system to ensure that the corrosion is under control. When a structure is not checked, a corrosion process can be triggered, causing structural damages despite the cathodic protection system, generating damages to the environment, public health, unexpected stops of a production process, etc. Nowadays, we use many remote monitorization systems, but it is still necessary to periodically record the data in order to ensure that the cathodic protection system operates correctly and supplies the adequate protection to the structure.

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